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DEPARTMENT OF THE ENVIRONMENT

Abatement of Pollution Due to Combined Sewer Overflows

J. MARSALEK

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INLAND WATERS DIRECTORATE
DEPARTMENT OF THE ENVIRONMENT
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Foreword

Pollution of rivers and lakes by overflows from combined sewer systems has been recognized as a major contributor to the lowering of water quality.

Conventional separation of sewer flows into sanitary and storm systems is extremely expensive and moreover may not eradicate the problem since storm water may be quite polluted.

At the Canada Centre for Inland Waters a programme to investigate combined sewers was initiated and the Hydraulics Unit undertook the literature review to determine the existing state of knowledge and to indicate possible future useful directions for research. Also consulted were the staff of the Environmental Protection Service at the Centre.

The programme of study ought to provide managers and engineers useful guidelines for amending existing systems and also lead to improved methods for treating flood flows in sewers.

T.M. Dick,
Chief, Hydraulics Division,
Canada Centre for Inland Waters.

Summary

Methods of abatement of pollution due to combined sewer overflows are critically examined. It is shown that the separation of sanitary and storm sewers may not yield the best solution in all cases. Some of the alternatives to sewer separation may be found to be more economical as well as more effective in reducing pollution. Possible alternatives to diminish volume or pollutional load of overflows by means of storage and treatment are described. The selection of the best abatement scheme will depend greatly on local conditions and will vary from situation to situation. Further research, especially on the treatment of overflows, is needed.

Introduction

1.1. The Problem

Combined sewers have dominated sewer design practices during the 19th and 20th century mainly because it was convenient and in the belief that the highly diluted sewage overflows from time to time were acceptable.

Treatment of all combined sewage at times of high flow is rather impractical with present technology and consequently the excess flow is diverted directly to the receiving waters. Generally, the design capacity of the sewage works is *two* to *five* times the dry weather flow (DWF), whereas during storms the flow can reach 100 times the DWF. Overflows occur at a level and frequency depending on the hydrologic characteristics of the area served by the sewer system, the hydraulic characteristics of the sewers and the amount of infiltration through bad joints and cracks in the piping.

With the increase in population, the overflow of combined sewers tends to be less and less acceptable to society. Consequently, today nearly all new sewer systems are designed to separate the sanitary flow from the storm water flow. This makes it quite feasible to treat the sanitary flow but accepts that all of the storm water will be discharged into the natural water courses.

Combined sewer overflows obviously add pollution to the water course and although the volume of raw sewage escaping treatment is 1 to 10% of the total volume nevertheless such overflows contribute as much as 50% of the solids and 30% of the BOD entering the water course after treatment of sanitary sewage (1, 2, 3).

Unfortunately, the storm water flow from separate sewer systems is not free from pollution and has been reported (4) to contain pollutants at levels up to 50-60% of those of sanitary sewer flows.

Overflows of combined sewers or storm water pollution is exacerbated by the shock effect to the receiving waters which can become overloaded and several days pass before recovery begins.

1.2. Costs of Separation

Conventional wisdom in the past has advocated separation of the sanitary and storm flow to provide full treatment of sanitary flow. Older systems, using combined sewers, can be converted to separate systems but this is clearly quite expensive.

Assessment of combined sewers in Canada has been done by Waller (5) during 1967-68 and the following information is from his report.

1) Combined sewers serve a total of 6.7 million people in Canada which represents 37% of the total or 54% of the urban population.

2) Nearly 90% of the population lives in 68 communities with more than 20,000 people.

3) Area served by combined sewers is 374,000 acres and contains a total pipe length of 8,568 miles.

4) About 60% of the combined sewers are more than 30 years old.

5) Cost of complete separation of combined sewers in Canada is $\$4.5 \times 10^9$.

Since 1967-68, when Waller gathered his data, there has been about a 24% increase in construction costs based on the Engineering News Record Index.

Thus one can estimate the total cost of separating sanitary and storm sewers as $\$5.6 \times 10^9$. The extremely high costs to separate existing combined sewers, about $20,000 per acre plus the disagreeable realization that storm waters are often quite heavily polluted, makes it imperative that a critical evaluation of the best means to reduce pollution loads be made. Various alternatives to separation of flows require assessment and comparison.

1.3. Problems and Abatement Methods

The present study, tends to concentrate on various alternatives to the separation of storm and sanitary flows in order to avoid overflows of combined systems and/or to reduce pollutional loads carried by the overflows.

Sewer systems are so varied and exposed to so many conditions that there is no universal panacea or solution to reduce combined sewer overflows. Rather, success is likely to be achieved by combining a number of beneficial actions. Note also that overflows cannot be entirely eliminated within economic constraints. For any selected level of flood flow there will occur at some time a flow of volume which is greater.

Thus a fundamental problem is the number of overflow occurrences which are acceptable in a given period. Intimately related to the frequency is the quality of the overflow which should be released to the water course. No fixed rule is available and this fact alone could result in quite different solutions to overflow reduction either in volume or quality. Problems could arise if better effluent quality is required after a system is constructed. There is a great need to establish quality criteria for overflows or for storm sewer discharges.

Various methods of overflow abatement are considered in more detail in the rest of the report under the following headings:

a) Separation of storm and sanitary sewage.

b) Reduction of overflow quantity and frequency.

c) Reduction of pollutional loads caused by overflows.

d) Combination of b and c.

Separation of Storm and Sanitary Sewage

Sewer separation is the conventional method of abatement of pollution due to combined sewer overflows. A schematic layout of a combined sewer system and a separated sewer system is shown in Figure 1. In the separate system, sanitary sewage is collected and conveyed separately from storm water in relatively small-diameter pipes to a waste-treatment plant. Storm water is carried by separate lines of large diameter. Among advantages of the separate system are: collection of all sanitary sewage; a high efficiency in the treatment process because washouts are prevented; good control of harmful organisms and bacteria.

Separated sewer systems are not without deficiencies. Firstly, the storm water passes directly to the water course and although it does not contain sanitary sewage as for a combined sewer, nevertheless the storm water can be quite heavily polluted.

Secondly, sanitary sewers can become overloaded during storm periods or after prolonged wet spells. Heavy infiltration can overload the system causing some sewage to bypass treatment. Flooding of storm sewers can result in ponded water entering the sanitary system through manholes causing flooding and backup.

Lastly, the presence of a biocide or harmful substance in the sewage can destroy the bacteriological processes in the treatment plant which then must bypass raw sewage until conditions are returned to normal.

Storm water runoff has been assumed in the past to be virtually unpolluted and thus could safely be discharged directly into water courses. In addition, the flow rates and volumes preclude treatment which encourages belief of the former view point. Recent observation and research (4, 6, 7) show that storm water contains polluting material but so far researchers have not been able to correlate the pollutional loads with the demographic and physical characteristics of urban watersheds.

Concentrations of pollutants in combined sewer overflows have been reported (4) in Table 1.

Other pollutional substances in storm water and overflows which have not received much attention in past are oil, lead, chloride, calcium and chromium. While the presence of oil and lead can be attributed to heavy traffic in urban areas, chloride, calcium, and chromium enter the urban runoff during de-icing operations in winter.

Not all urban precipitation in winter is conveyed to water courses by sewers, but part of it, in the form of snow, is collected from roads and streets and dumped directly in rivers or lakes.

Recent research (6, 8, 9, 10) shows that rain water may contain significant levels of pollutants because apparently rain scavenges some substances present in air. The interdependency of various pollution-control programs is shown here and it follows that reduction of air pollution should have some effect on the trace metals in storm water.

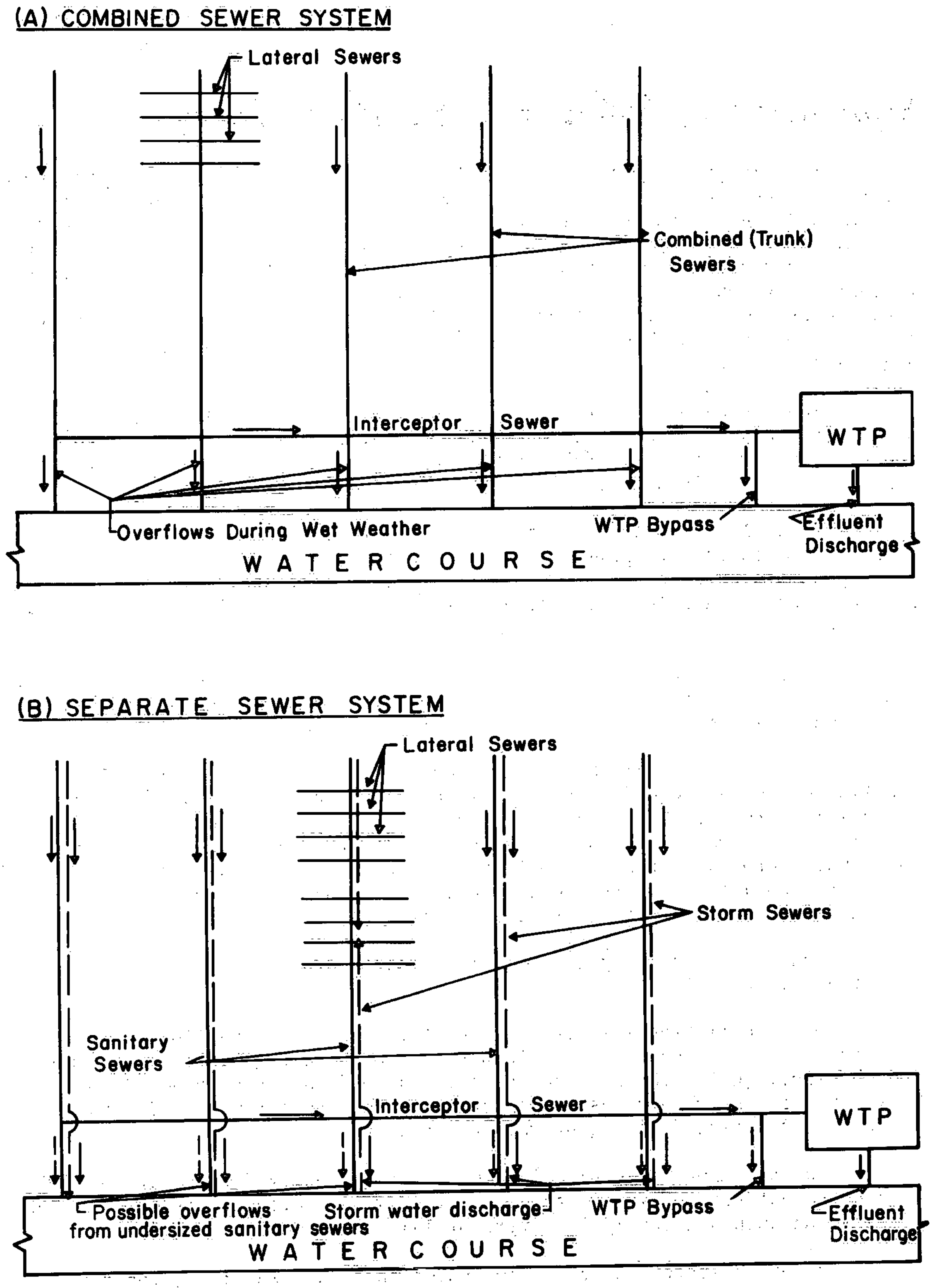


Figure 1. Sketch of (A) combined sewer system and (B) separate sewer system.

TABLE 1

Pollutants in Combined Sewer Overflow

1. Solids - Common concentrations range from 200 to 2,500 mg/1, and highest reported concentrations were over 12,000 mg/1. About 2/3 or even more of the total solids are in suspension.

2. BOD - Reported concentrations of BOD vary considerably and it is difficult to present any meaningful value. High variation of reported BOD concentrations is partially due to the fact that BOD (as well as some other pollutants) varies significantly with time during the storm runoff. BOD concentrations may be estimated, with the above reservations, to range from *5 to 60* mg/1, with peak values of limited duration exceeding the upper limit up to *ten times*.

3. COD - Average reported concentrations range from 40 to 140 mg/1.

4. Bacteria - Typical bacteriological counts range as follows:
   a) coliform 5,000 - 200,000/100 ml
   b) fecal coliform 400 - 300,000/100 ml
   c) fecal streptococcus 4,000 - 200,000/100 ml

5. Nutrients - Since the concentration of nutrients in storm water is only a fraction of that in sanitary sewage, overflows are not usually considered to contribute a significant amount of nutrients.

To illustrate the possible extent of pollution due to urban runoff in comparison to other sources, the following example which lists pollution sources for an area studied in Atlanta, Georgia, is given in Table 2 (11).

In the case cited in Table 2, the urban storm runoff is not treated because it would not be feasible nor economical although according to the figures, it represents 64% of the total annual BOD output entering a local watercourse.

It is quite evident therefore that separating the sewer system is not a universal panacea for pollution problems. It can be inferred from Table 2, that if the sewer system is changed from combined to separated then the total BOD released per year would drop about 30%.

Thus the reduction in pollutional loads by separating sewers has finite limits and in some cases the reduction may not be worth the price.

TABLE 2

BOD Loads in Atlanta

	Pollution Source	Lbs. of BOD/Year	% Total
A.	Storm drainage from urban areas (22,042 acres)	5,577,000	64%
B.	Combined sewer overflows to Intrenchment Creek (3,550 acres)	1,633,000	19%
C.	Bypassing of flows from Intrenchment Creek Interceptor	506,000	6%
D.	Combined sewer overflows at McDaniel Street (968 acres)	445,000	5%
E.	Intrenchment Creek waste treatment plant effluent	185,000	2%
F.	Bypassing of South River waste treatment plant	183,000	2%
G.	South River waste treatment plant effluent	146,000	2%
	TOTAL	8,675,000	100%

2.1. Feasibility of Sewer Separation

2.1.1. Complete Separation

Methods of sewer separation in existing systems are pictured in Figure 2. Sewer separation can be accomplished in two ways: Firstly, as illustrated in Figure 2A the existing combined sewers are used only as sanitary sewers and new storm sewers are constructed. Secondly, as in Figure 2B the existing sewer system can be used as storm sewer, and new sewers constructed to carry sanitary sewage. The pipe carrying sanitary sewage (of smaller diameter than storm sewer) is usually placed a few feet below the existing combined sewer so that the existing house or other laterals can still be connected. It is also possible to use a pressurized sanitary sewer which may also be located inside the combined sewer pipe (Fig. 2C).

2.1.2. Partial Separation

Previously described sewer separation methods dealt with complete sewer separation. However, the system described as 2A, i.e. use of the existing combined sewers as sanitary sewers and construction of new storm sewers, may be modified to give the so-called partial sewer separation. Abatement of pollution due to combined sewer overflows by partial sewer separation has been proposed for Toronto (12), and would be accomplished by building a new system of road sewers which would carry significant portion

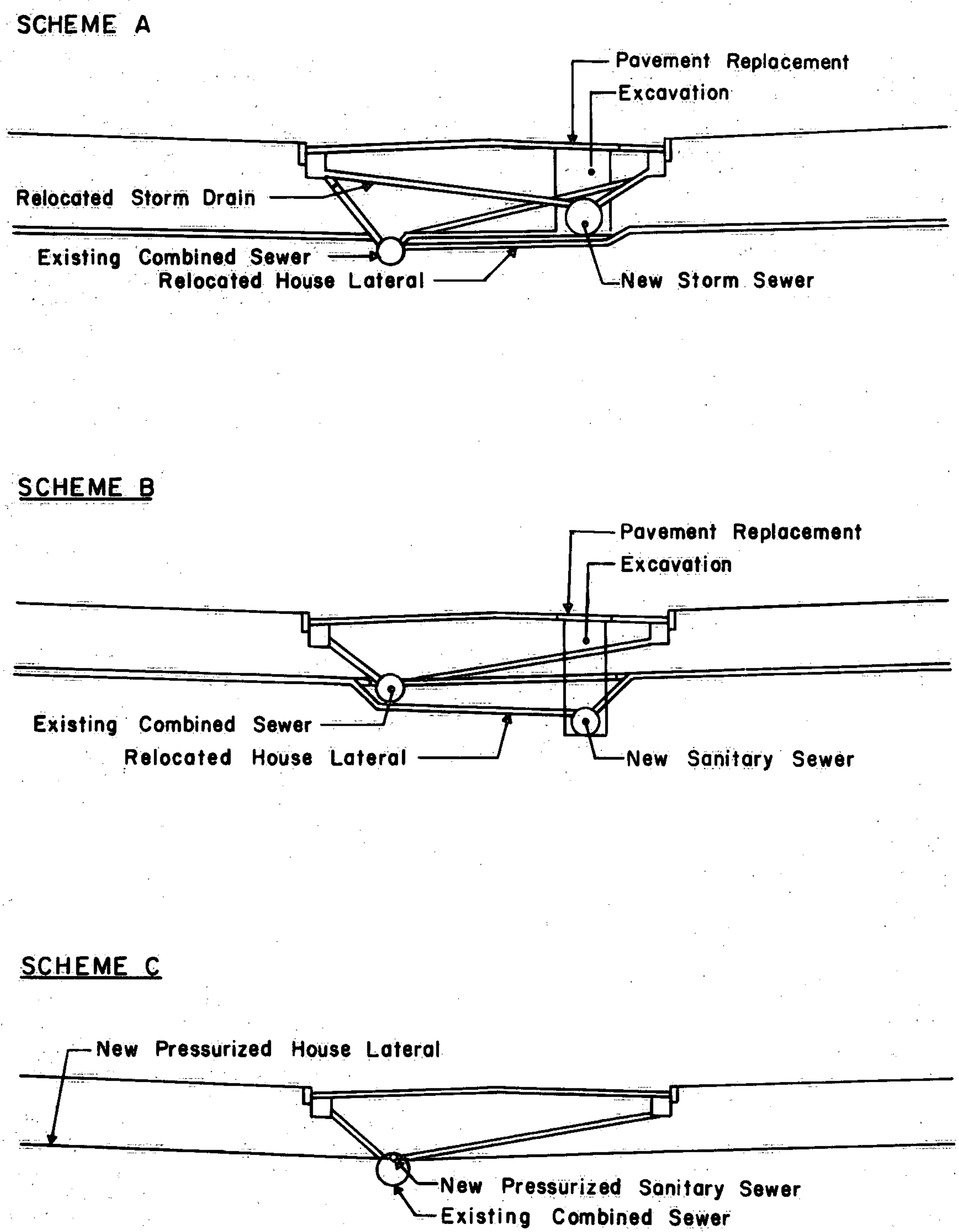


Figure 2. Various schemes of sewer separation.

of urban runoff originating from roads, parking lots and other impervious areas. Storm water from roofs would continue to enter the existing combined sewers.

Another form of partial sewer separation is the construction of so-called "express" sewers (5), which convey sanitary flows from new developments, where separate sewers have been constructed directly to the treatment plant. Loadings in downstream sewers are less and overloading is less likely to occur. However the treatment-plant capacity must be increased.

Though the partial sewer separation is not an ultimate solution to the problem of combined sewer overflows, it can be very useful as a means to decrease the volume and frequency of overflows. Partial sewer separation is often economically attractive, since it costs about 50% of the price of total separation mainly because no work has to be done reconnecting laterals and house connections. Partial separation may therefore be found feasible, especially in those cases where the hydraulic capacity of the existing sewer system is insufficient and the cost of full separation is beyond financial means of the community.

2.1.3. Pressurized Sanitary Sewers

Suspension of a pressurized sanitary-sewer line (2C) inside existing combined sewers has been studied in several ASCE research projects (13). This idea has been investigated using steel pipes (14). Suspending a pipe of diameter D_1 inside a large pipe having diameter $D_2 = 5.8\ D_1$ reduced the large-pipe flow capacity from 4.5 to 12.7% depending on the eccentricity of location of the pressure pipe.

To make such a system hydraulically feasible, the diameter D_1 has to be relatively small and to obtain sufficient flow it is necessary to pump through a pressurized sewer. Though the principle of pressurized sewers has been proved technically feasible in several ASCE demonstration projects (13), the costs of pressurized plumbing, pumps and grinders located in every dwelling is prohibitive. Unit costs as high as $113,000/acre have been quoted (15) for a gently sloping heterogenous commercial area in Boston. Such high costs generally eliminate in practice the use of pressurized sewers as a solution for sewer separation.

Conclusions - Sewer separation is a widely accepted method of control of pollution owing to combined sewer overflows. Past acceptance is not due to its previously mentioned advantages, but also due to the fact that sewer separation was the only known method of pollution control of the overflows. For this reason, the cost of sewer separation is commonly used as a base to judge the economical effectiveness of other means to reduce pollution by combined sewer overflows. Some of the alternatives to sewer separation might prove to be less costly or more effective in pollution control than sewer separation. However in comparing sewer separation methods, the least expensive is partial sewer separation which costs about $10,000 per acre; then follows the use of existing sewers as storm sewers and the construction of new sanitary sewers; and the most expensive is the use of existing sewers as sanitary sewers and the construction of new storm sewers.

It should be borne in mind that sewer separation should probably not be applied as the universal method of abatement of pollution due to combined sewer overflows. Alternate methods of overflow abatement should be considered to obtain the most satisfactory and economical improvement.

The intercomparison of various abatement methods can be aided by mathematical models of the management of urban runoff. Most advanced seems to be the Storm Water Management Model developed by EPA (U.S. Environmental Protection Agency) (63).

CHAPTER 3

Reduction of Overflow Quantity and Frequency

This chapter examines pollution abatement methods which reduce the quantity and frequency of occurrence of overflows by the modulation of urban runoff and the sewer hydrograph through various technical and policy measures. Peak sewer discharges can be reduced by providing physical storage in the sewer-line system. Inflow rates of storm and other waters into sewers can also be reduced by increasing concentration times or by adopting procedures or regulations which affect the supply of runoff and sewage. A critical review of municipal regulations and design practices could possibly bring about reductions in sewer flows.

3.1. Control of Inflow and Infiltration

Control of inflow and infiltration into sewers has been studied in detail by the American Public Works Association (16, 20) which proposed the following definitions of inflow and infiltration:

> "Inflow", includes the volume of water discharged into sewer lines from such sources as roof leaders; cellar and yard area drains; foundation drains; commercial and industrial so-called clean water discharges; drains from swampy areas; etc. It does not include, and is distinguished from, infiltration.
>
> "Infiltration", includes the volume of groundwater entering sewers and house connections from the soil, through defective joints, broken or cracked pipes, improperly made connections, manhole walls, etc.

3.1.1. Policies to Reduce Inflow

Sewer systems may be receiving more inflow than provided for in their design because of illegal connections. If the practice is sufficiently widespread, surcharging will occur frequently and cause flooding in basements and overflows. In addition the increased volume of sewage adds to treatment costs and possibly pumping costs. There are indirect costs because the overloading prevents further development and simple extension of the sewer system.

The existing policies regarding the connections of various sources of inflow to sewer systems vary from locality to locality. In some communities, connections of roof leaders, cellar and foundation drains to combined or even sanitary sewers are legal, or if these connections are illegal, no attempts are made to locate them and to enforce their removal. The revision of municipal policies regarding the sewer-use ordinances and regulations, as well as the enforcement of a new policy, is probably highly necessary. Enforcement of regulations is often resisted by private property owners because of the additional expense involved in complying with the by-law after illicit connections have been made. Costs of inspection to detect illegal or other non-advantageous connections may be rapidly off set by the savings made in treatment costs. Such was the case in Springfield, Illinois (17) where roof downspouts from domiciles were connected to the sewer system. Identification of the offending spouts cost the City about $5.00 per house. Based on two very conservative estimates, this cost would be returned in 2.5 years by savings in sewage treatment and services.

Detection of illegal connections may be difficult but closed circuit television and smoke tests have been employed to advantage.

An unusual solution for the disposal of rain water was applied in Canton City (18) where a large service centre, built in an area without storm sewers, disposes all storm-water runoff into a system of dry wells which allows the runoff to infiltrate into the ground. Though the feasibility of such a system depends on local geological conditions, it is worth consideration for application elsewhere.

Some consideration has to be given to so-called clean waters which originate in commercial or industrial establishments and are not heavily polluted. One of the major sources of such waters is water-cooled condensers used in air-conditioners and refrigeration equipment. Average water consumption of a water-cooled condenser can be estimated at 3000 gallons per day per ton of refrigeration capacity (i.e. 12,000 BTU/hr.) (12), which is equivalent to the volume of domestic sewage produced by about 40 people (considering domestic sewage output as 75 gal/per head). It can be seen from this example that water-cooling operations can use up a significant part of sewer capacity, and that connection of such units to sanitary combined sewers is quite undesirable. However, municipalities do often have regulations forbidding the disposal of cooling water in this way and refrigerant installations must recycle the water.

In summary, depending on local conditions the effect of inflow on combined sewer overflows should be evaluated, and if the disconnection of various inflow sources from a sewer system is found economically feasible and does not endanger private properties, then such disconnections should be implemented. Drainage problems have to be solved permanently without using up the capacity of sanitary or combined sewers. Experience shows that the moderate expenses for the enforcement of sewer ordinances and use policies are rapidly recovered by savings on sewage treatment, savings in the construction of new sewers, and reductions in the volume of sewer overflows.

3.1.2. Undersizing of Storm Water Inlets and Storm Sewers

One possibility of modulating storm runoff and decreasing peak flow in sewers is to increase time lag of the runoff by intentionally undersizing the storm-water inlets into the sewer system and by limiting the size of storm sewers. Though such a practice leads to temporary surface ponding of storm water and therefore, may not be acceptable in densely populated areas, this idea may be applied in special cases.

Successful application of undersized storm sewers is reported in Reference 19 which describes a drainage system for an airport at Denver, Colo. By undersizing collectors and inlets, the peak flow in the sewer system was reduced and overloading of the existing sewers was avoided. Excessive storm water was partially detained on surface for a limited time and partially infiltrated into the ground.

Another idea to increase the time lag of roof runoff from large buildings is to pond the water. Roof ponding of storm water, if feasible aesthetically and structurally, can be very effective in increasing time lag of the runoff from flat roofs, especially when gutter inlets are fitted with cylindrical weirs (Fig. 3).

In general increasing the time lag of storm runoff will reduce peak flows in sewers which will result in the reduction of the volume of overflows from combined sewers receiving the storm runoff and also reduce the design flows for storm sewers in a separate system.

3.1.3. Reduction of Infiltration into Sewers

The problem of infiltration is similar to the preceding problem of inflow in its effects on sewer flows. The amount of infiltrated water can be enormous. It is estimated (16) that infiltration may average as much as 15% of the flow and can rise to 30% of the total flow. Such vast volumes of extraneous water not only increase operational and capital costs of the waste treatment plant, but also often cause sewer overflows from combined as well as sanitary sewers. The latter case as reported in Reference 21 describes an engineering study of the separate sewer system in the city of Roanoke, Va. The study found that sewage overflows from the separate sanitary sewers were caused mainly by excessive infiltration into sanitary sewers. The rate of infiltration was found to be proportional to the average rainfall intensity and reached values as high as 24,000 gallons per inch of pipe diameter per mile per day which is about 50 to 100 times the normally specified infiltration allowance. The study recommended the reduction of infiltration by 80% as the main measure to control overflows.

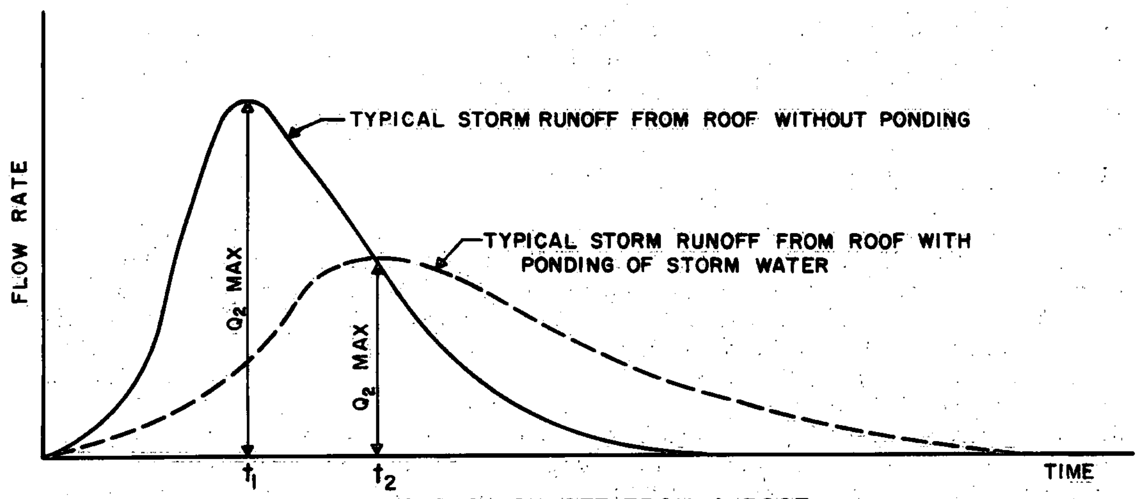
The problem of infiltration is encountered in both existing sewers and newly designed sewers. In the former case, infiltration and its reduction should be measured and considered as one means of overflows control. Techniques, such as closed circuit TV, movie cameras, smoke tests, offer ways to locate defective spots in the sewer system. Among the methods to correct defective components are: replacement of sewer sections (the most expensive but sometimes the only solution) sealing of leaks by chemical grouting and relining of large diameter defective pipes by inserting plastic liners.

In case of new sewers, the report by American Water Works Association (20) recommends the following actions. Infiltration allowances should be stricter, pipe materials should be selected not only from the structural point of view but also from the point of view of infiltration, watertight flexible joints should be used, better techniques should be developed for trench preparation and sewer laying, and sewer pipes should be carefully inspected during installation.

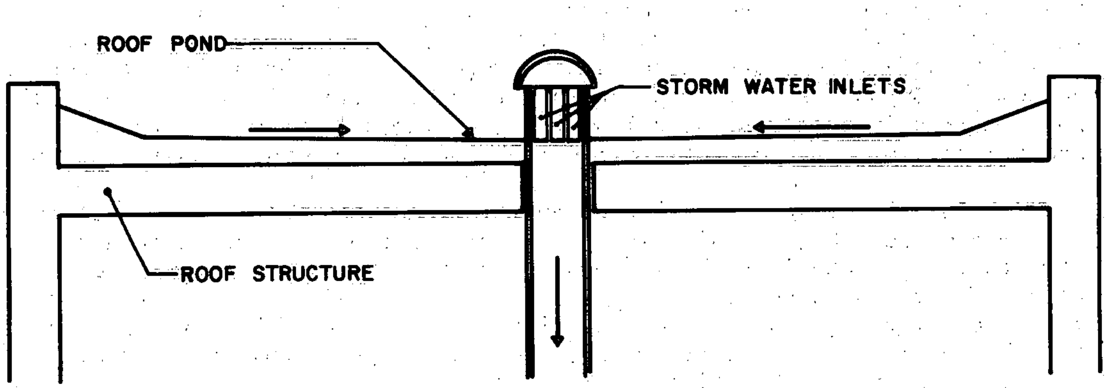
In conclusion it should be mentioned that though the cost of repairs of defects causing high infiltration is relatively high (average estimate, from Reference 16, is about $15 per lin. ft.) the possible future requirements for more intensified treatment of sewage will tend to make the control of infiltration and inflow an economic necessity.

3.2. Optimal Sewer Flow Control

An optimal sewer flow control is a regulatory system which utilizes the sewers and waste-treatment plant to their full capacity and allows sewage overflows only in absolutely unavoidable cases. Sewer flow control can be achieved by rational installation and operation of diversion structures, maximum utilization of in-system storage, and increasing sewer flow capacity by drag reducing additives.



EFFECT OF ROOF POND ON RUNOFF FROM A ROOF



SKETCH OF A TYPICAL ROOF POND (ELEVATION)

Figure 3. Roof ponding of storm water.

3.2.1. Sewer Flow Control by Overflow Regulators

Overflow regulators are devices which protect collection lines, interceptors and sewage pumping and treatment plants against overloading by diverting excessive sewage flows. The main operational requirements for regulators are: effective flow control, trouble-free operation, easy and inexpensive maintenance and moderate capital cost.

A recent survey of combined sewer regulators in Canada and the U.S.A. by the American Public Works Association (22) revealed rather unsatisfactory conditions for existing regulators and an urgent need for improvement. For example, regulator malfunctions could allow overflow in dry weather or in addition to this could extend the overflow operation beyond the point when the interceptor feeding the plant could handle the sewage flow. In order to identify the susceptibility of individual types of regulators to malfunctions as well as the reasons for these malfunctions, the survey evaluated the operation and maintenance of common regulators.

3.2.1.1. Static Regulators

Typical of static regulators are: overflow weirs, side-spill weirs, leaping weirs, orifices, syphons and manually adjustable gates. These regulators are relatively inexpensive and trouble free but unfortunately the regulation achieved is not always satisfactory compared to dynamic regulators.

According to British practice, the best static regulators are high side spill weirs of which details can be found in Reference 24. It has been suggested (23) that static regulators may be acceptable for flows up to 2 cfs but for greater flows a controllable regulator should be used. In some cases it may be feasible to replace several relatively inefficient static regulators with one dynamic regulator.

3.2.1.2. Dynamic Regulators

Typical of these are: float-operated gates, tipping gates, cylindrical gates, motor-operated gates, hydraulically-operated gates, fluidic regulators, inflatable dams, Ponsar syphon.

Dynamic regulators usually provide good regulation of flow but regular inspection and maintenance is necessary. Automatic regulators are highly susceptible to electrical and mechanical breakdowns because of the damp corrosive environment in the sewers. Furthermore, capital costs for dynamic and automatic regulators are high compared to static types.

Despite these shortcomings, automatic regulators are often used in the downstream parts of sewer systems, where proper regulation, and consequently, protection against surcharging is of greater importance. Attempts to correct the shortcomings of conventional automatic regulators led to the development of new types, namely, the Ponsar siphon, the inflatable fabric dam and the fluidic regulator (see Fig. 4). All of these new regulators are remotely controlled, relatively inexpensive, and easily serviced and maintained. The most promising seems to be the fluidic regulator (25, 26) which was developed in the U.S.A. The regulator operates on the fluidic principle which uses the phenomena that a jet will attach itself to a wall. Main features of this latter regulator are its excellent regulation performance, low initial cost, simplicity, absence of moving mechanical parts, and low space requirement.

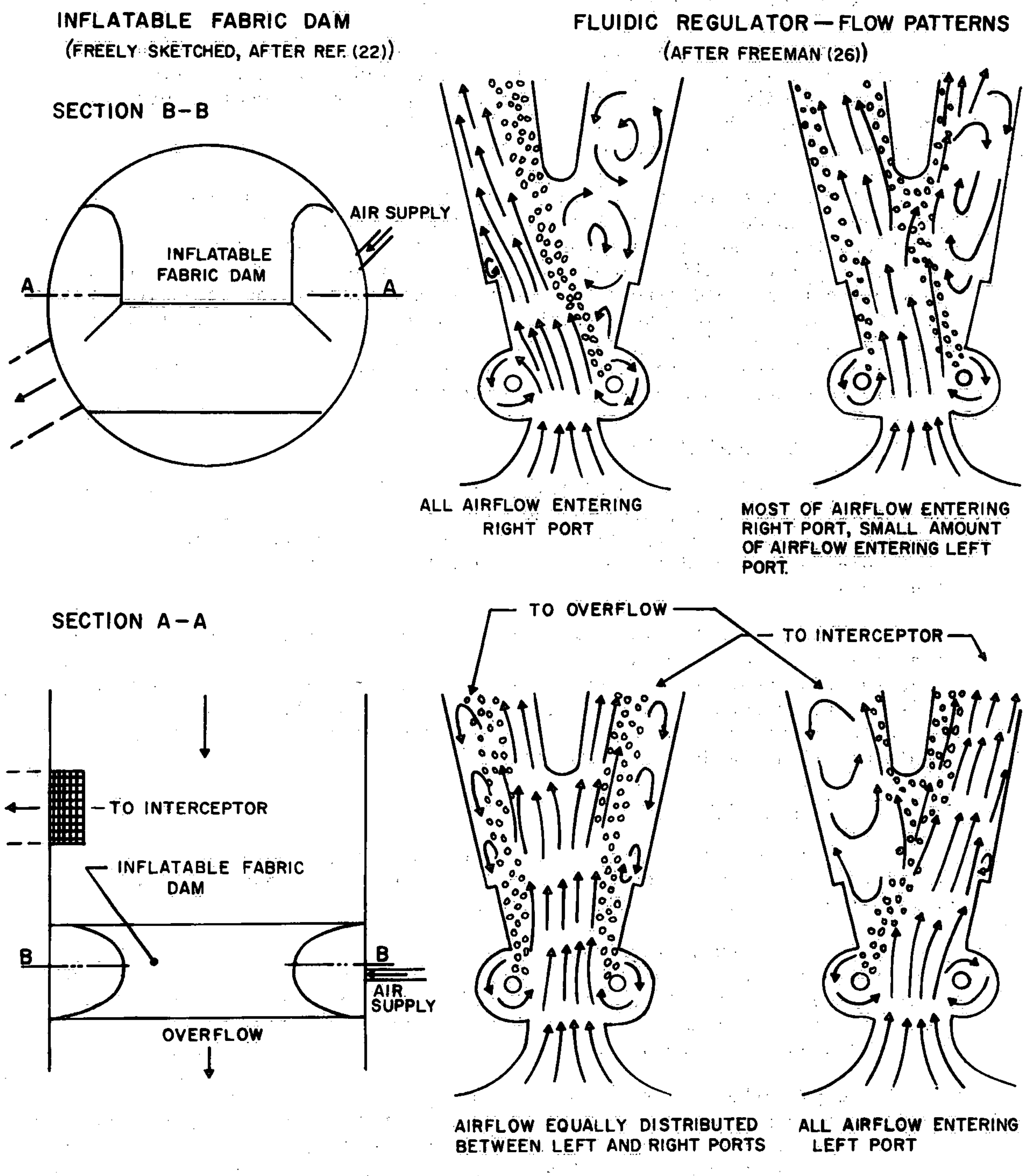


Figure 4. Modern overflow regulators - inflatable fabric dam and fluidic device.

The future of this regulator in sewer control may depend on the results of its demonstration tests, which started in the spring of 1971. Two testing locations were selected, one in Philadelphia, Pa., and the other in Akron, Ohio, with peak flows of 2 cfs and 25 cfs, respectively. The capital cost of a fluidic regulator is only about 10% more than that of a comparable simple static regulator. Replacement of an existing static regulator with a fluidic regulator should cost only about one fifth of the cost of more conventional designs.

3.2.1.3. Regulators Controlling Overflow Quality

There is one special group of regulators which has not been mentioned in the previous classification. These regulators control not only the quantity but also the quality of overflows. Recent research of overflow regulators in Europe (23) was aimed at the development of diversion structures which would not only control the diversion of flow from the interceptor but also improve the quality of overflowing sewage by trying to keep a maximum of solids in the interceptor. Among these types of regulators belong vortex regulators, stilling-pond regulators, spiral-flow regulators and weirs equipped with racks, screens and skimmers. Further investigation of these regulators is required, before they may be adopted or completely rejected. A recent report (27) by the Technical Committee on Storm Overflows and the Disposal of Storm Sewage (appointed by the Minister of Housing and Local Government, U.K.) indicates that vortex and stilling-pond regulators do not improve the water quality of the overflows to an extent which would justify the greater cost of these regulators.

Summary - It is believed that the idea of reducing the concentration of pollutants escaping through overflows by hydraulic principles or new technology deserves to be pursued further. Detention of solids in the interceptor would reduce the solids passing into the water course or into temporary storage or holding tanks.

Replacement of outdated diversion structures by better regulators is one of the first steps which should be considered in planning the control of pollution due to combined sewer overflows. The usefulness of upgrading sewer regulators can be illustrated by an example from Atlanta, Ga. (11). An engineering study of combined sewer overflows revealed that the replacement of two old static regulators by new dynamic regulators at the cost of $50,000 would reduce the annual BOD load carried by the overflows into a local watercourse by 25%. The cost of this abatement choice (expressed in dollars per removed lb. of BOD) was only about 1/25 of the cost of the next cheapest possibility, i.e. small storage and treatment, achieving the same BOD-load reduction.

3.2.2. Control of Combined Sewer Overflows by Increased Interceptor Capacity

The question of controlling combined sewer overflows by enlarging the interceptor might arise during reconstruction of existing combined sewers, or possibly when a new combined sewer system is being designed. Accordingly, a brief discussion of this alternative is included here.

For economic reasons, the design flow capacity is usually in the range 1.5 to 5 times dry weather flow (DWF) with the majority of interceptors having the capacity 2-3 DWF. The latter range of capacities yields sewage collection efficiencies between 96 to 98% in most cases. The remaining 2 to 4% of sewage escapes in the form of combined sewer overflows. The relation between the interceptor sizing and the volume or duration of the overflows was determined for several North American cities and reported in References 2, 12, 28. Clearly, the volume of overflows during wet weather is maximum for an interceptor capacity equal to DWF (i.e. no capacity is reserved for storm water), and decreases with increasing interceptor capacity. One set of data from Reference 12 was recalculated and plotted in a new form in Figure 5. Curve A in Figure 5 represents the relationship between the interceptor capacity expressed in multiples of DWF and the percentage retained of sewer overflow above DWF (i.e. that fraction of sewage which after dilution by storm water escapes by combined sewer overflows). Thus for interceptor of capacity equal to 1 DWF, the maximum volume of sanitary sewage is lost and in the example under consideration, this was 12% of the total annual sewage flow during wet weather. An interceptor of capacity of 1.7 DWF as shown in Figure 5 reduces the sanitary sewage loss by 50%. Although the graph was plotted for a specific location and conditions, it illustrates one characteristic tendency. The interceptor efficiency, in reducing the sanitary sewage loss during wet weather, falls off for interceptor capacities higher than about 2.3 DWF. The interceptor efficiency (i.e. rate of interception of sewage loss per capacity of 1 DWF for various sizes of interceptor) was plotted as curve B in Figure 5. Curve B was derived from curve A by dividing the rate of interception of sewage loss by interceptor capacity expressed in multiples of DWF. Due to the low collection efficiency and the high cost of large interceptors, any increase of interceptor capacity above the common range 2-3 DWF cannot be recommended as an effective control of pollution due to combined sewer overflows. Furthermore, any increase in interceptor capacity requires a corresponding increase in the size and cost of the waste-treatment plant.

3.2.3. Increase of Sewer Capacities by Drag-Reducing Additives

In some cases, a combined sewer overflow during wet weather can be caused by a constriction ("bottleneck") in the sewer line which leads to sewer surcharging, backflooding, and eventually, to overflows. This situation is pictured in Figure 6, where only the section "S" of sewer line between cross-sections 2 and 3 has insufficient capacity due to sewage inflow Q_2 which could be connected to the sewer system during later development. Surcharging of section "S" then causes overspill of sewage through an overflow. This type of problem can be solved by application of drag reducing additives. One group of these additives are water-soluble polymers. Several polymers have been investigated (29, 30, 31) to determine their effects upon flow characteristics of sewage, operation of waste-treatment plant, and aquatic flora and fauna. It was found that by adding 45-200 ml of polymer per liter of sewage (i.e. volume concentrations 4.5-20%), depending on the conditions, the original discharge could be increased up to 2.5 times without increasing the energy loss. Economic analysis of polymer application indicates that the average annual cost of adding polymers during peak storms is about 1/5 - 1/2 of the average annual cost of installing an additional sewer.

Though the reported tests have not revealed any adverse effects of the polymers on sewage bacteria, aquatic life, and algae in water courses, nevertheless polymer addition to sewage, in the rather large quantities required, does not seem to be suitable as a long-term solution. Polymers in water bodies could create unforeseen problems with regard to ecology and sediment transport which would be better avoided.

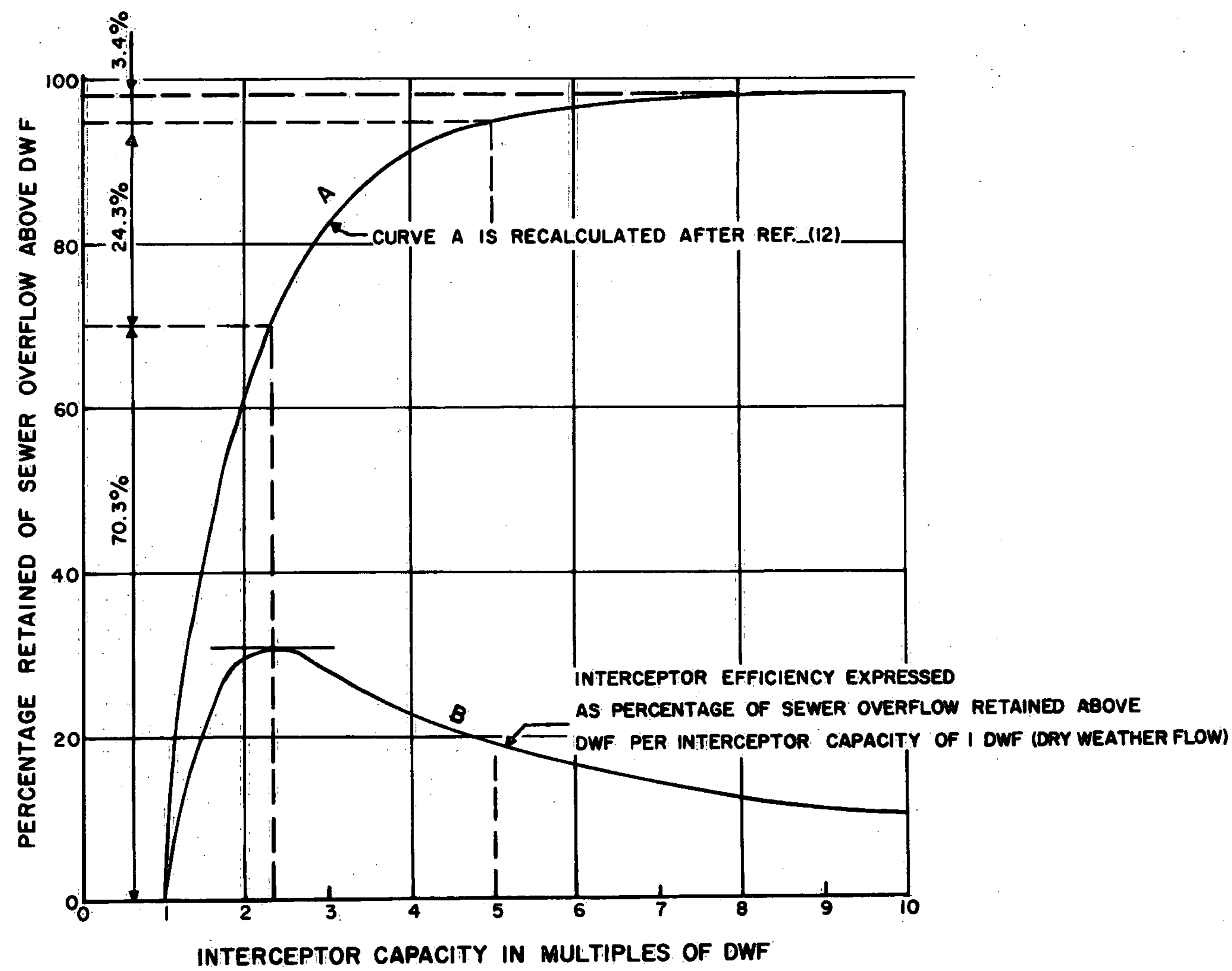


Figure 5. Percentage of sewer overflow retained above DWF vs. interceptor capacity.

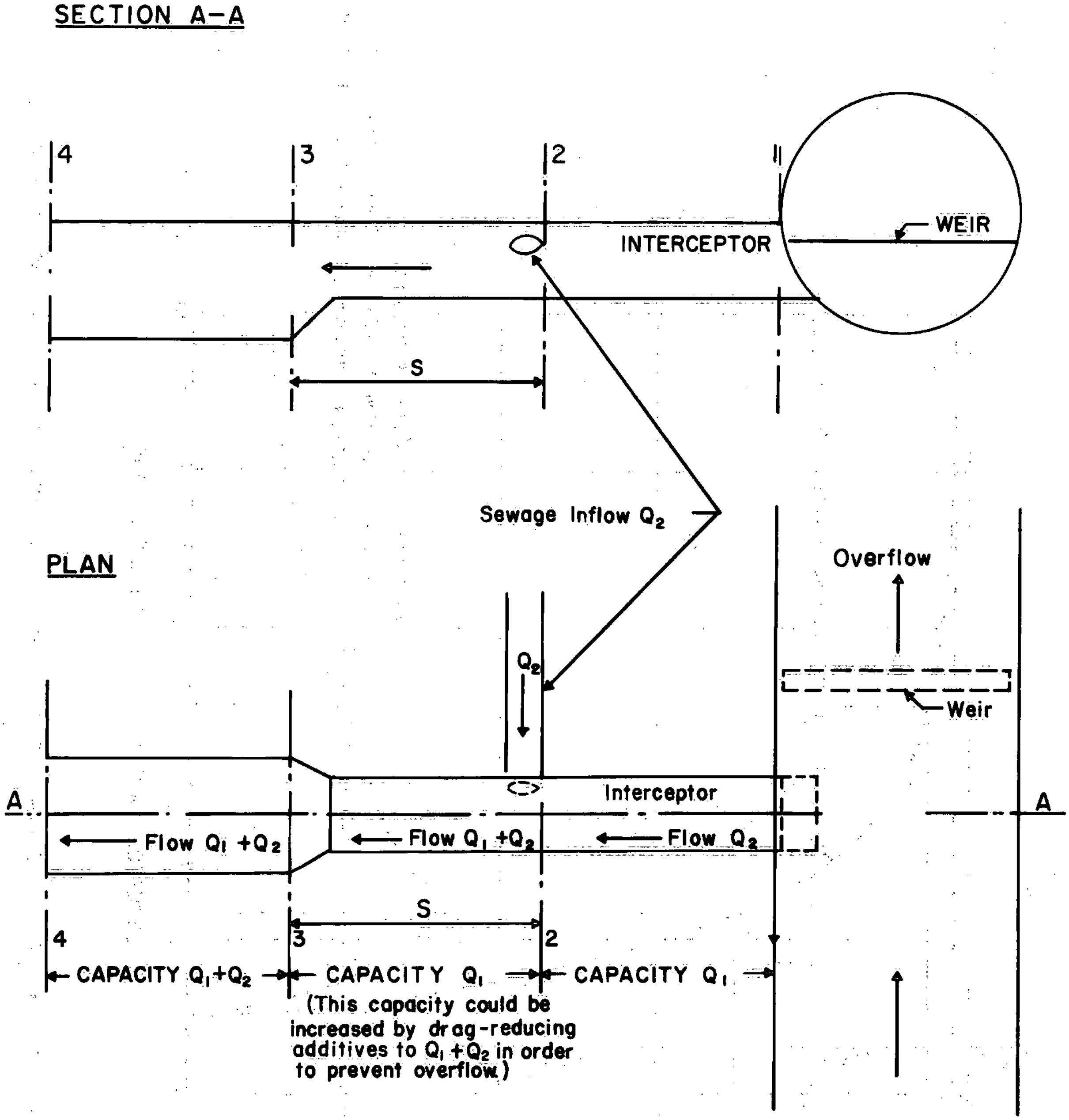


Figure 6. Sewer configuration suitable for application of drag-reducing additives to sewage flow.

3.2.4. Computer-Augmented Treatment and Disposal System (CATAD System)

CATAD is the most advanced and sophisticated method of operation of an existing sewer system aimed at minimizing the volume, frequency and pollutional load of combined sewer overflows. This system is only suitable for large metropolitan cities, and at present, is under development at three U.S. cities, namely, Detroit, Minneapolis-St. Paul, and Seattle.

A typical CATAD system includes the following items of equipment (32):

1. Peripheral monitoring and telemetering stations.
2. Transmission system.
3. Central computer.
4. Operator's console.

Monitoring and telemetering stations are located throughout the whole drainage area and monitor receiving water quality (DO, temperature, pH, conductivity, turbidity, etc.), rainfall data, flow through sewers, operational condition of overflow regulators and quality of overflows. Data is transmitted, usually by leased telephone cables, to the central computer which processes the data and calculates an operational strategy to minimize overflows. Data processing consists of predicting sewage flows in the individual parts of the sewer system by taking rainfall data, routing the flood waves through the system, and allowing sewage to overflow at those locations where the concentration of pollutants in the combined sewage is lowest and will cause least harm to the receiving waterbody.

The operator's console and wall map display serve as the interface between the operator and the control system. Lights on a display map show control stations in operation and if conditions exceed predetermined limits as calculated, then action is taken by the operator. In future, the control of the system will be performed automatically by the central computer.

The CATAD system has the following operational features.

a) Storm flow can be anticipated. According to the rainfall areal distribution, certain parts of the sewer system where large runoff of storm water is expected to arrive can be partially emptied by the appropriate use of control gates.

b) Storage available within the sewer system can be utilized to the full. Sewage flow can be diverted from parts threatened by surcharging and overflows to other parts of the system which are not yet filled to maximum capacity. Also sewage flow from upper catchments where rainfall inflow has ceased can be completely shut off so that overloadings further downstream need not occur.

c) Sewage can be selectively retained. When an overflow becomes absolutely necessary, it is possible to select the combined sewage which has lowest pollutional load. This operational feature is especially important for intercepting and retaining in the system the "first flush" which has the highest concentration of pollutants.

d) Overflows can be restricted to the least harmful locations. Unavoidable overflows can be let go at those locations which are least critical with regard to aquatic life or are distant from public beaches and other recreational facilities.

Though CATAD system has undisputable advantages and the ability to reduce pollution due to combined sewer overflows, it is only applicable in large metropolitan communities having large drainage areas and fair capacity of the sewer system. Over a large drainage area, the rainfall intensity and duration can vary significantly which is essential for maximum utilization of all CATAD features. In small communities which would have more uniform areal distributions of rainfall, such operational features as storm sewage flow anticipation or diversion of sewage flows within the system are hardly applicable. Smaller communities, however, could install certain items of CATAD systems such as stations which monitor operation of overflows (33). Such a monitoring system could direct maintenance crews to malfunctioning regulators which remain in operation too long or fail to shut off during dry weather.

3.3. Retention of Combined Sewer Overflows

Retention of combined sewer overflows is the storage of overflows without any treatment. After the wet weather and high sewage flows subside, the stored overflow is returned to the interceptor where it is conveyed to the waste-treatment plant for treatment. In the literature the terms retention tank, detention tank, or stormholding tank are essentially the same since all of them refer to a storage tank which holds storm water or combined sewage, and under various circumstances, can act as retention or detention tank.

3.3.1. Retention Basins

Retention basins or tanks, have been adopted by many communities as a control measure to abate pollution due to combined sewer overflows. Design of these basins usually requires consideration of the following points.

a) Basin capacity required to give a selected level of protection to water course.

b) Basin location and structure.

c) Deposit of solids in retention tanks and basins.

d) Economics of various alternatives.

While the first point will be discussed in Chapter 5, the other points are briefly discussed here.

Experience with design and construction of retention basins shows that their location is usually selected by the availability of construction sites as well as by the public acceptance of these structures. Where no land is available, retention basins have sometimes been built as off-shore structures located either above or under water. New materials introduced into construction practice make it economically feasible to build retention tanks of rubber, nylon, or fiberglass reinforced plastics.

Public acceptance has to be considered in the selecting of sites for retention basins. Unsightly buildings or structures or objectionable odours are common problems. Experience shows (2) that both these problems can be solved. Odour emission can be controlled with enclosed retention tanks and visual pollution avoided by good architectural design. One city reports (34) that the public acceptance of a storm-holding tank in a residential area was won by disguising this tank as a residential dwelling.

Solids suspended in the sewage tend to settle in the retention tank. Deposited solids not only gradually fill up the basin, but also cause depletion of the oxygen and the emission of odours especially if the solids become exposed to the atmosphere. Settling of solids can be coped with in two ways. Either the solids are kept in suspension by hydraulic means or the basin is equipped to remove solids. Coarse solids may be prevented from entering the basin by racks or screens and fine solids contained in the sewage may be kept in suspension inside the basin by artificially induced circulation (35). This solution is economically feasible for small circular tanks. Removal of solids from basins may be accomplished by hydraulic or mechanical means. The cost of solids removal from retention basins adds to the operational expenses.

After the overflow has stopped, the contents of the retention basins are returned to the sewer system either by pumping or by gravity flow. The waste-treatment plant has to have the capacity to handle the volume of stored sewage discharged over several hours (6-10 hrs) in addition to its DWF. Retaining the overflow longer than absolutely necessary leads to oxygen depletion in the stored sewage and also increases the probability that a second storm could occur for which insufficient storage would be available.

Some further information pertinent to retention basins is contained in Chapter 5 under the paragraph headed Stormholding Tanks.

3.3.2. Underflow Deep Tunnels Collecting Overflows

Underflow tunnels may function as retention basins. Overflows from combined sewers drop through shafts into the underflow tunnel which is located well below buildings and water courses. Later the sewage is pumped to the waste-treatment plant when the plant inflow declines.

Though the construction of deep tunnels and the pumping is costly, this solution may be acceptable in cases when no sites for sewage storage are available. Such was the case in Chicago (36), where the high population density precludes sewer separation or the construction of storm holding tanks. The plan adopted consists of 35 miles of conveyance tunnels, 26 ft. wide and 50 ft. deep, excavated in solid rock beneath the Chicago, Calumet, and Des Plaines Rivers, and beneath the Sanitary and Ship Canals. Overflows collected by the tunnel are to be pumped during off-peak hours to three existing waste-treatment plants. The tunnel was designed to handle the runoff from a 100-year storm.

It is believed that due to high capital and operational costs, deep underflow tunnels are not feasible for small and medium communities. In large cities this solution has the great advantage that the construction of the deep tunnels does not disrupt city life.

3.4. Upgrading and Increasing Capacity of Waste-Treatment Plant

The overflow of combined sewers or the bypassing of treatment plants is sometimes necessary to protect the waste-treatment plant from hydraulic or pollutional overloading. Overflows and bypassing are practically identical phenomena with respect to the adverse effects on the receiving waters. While overflows generally occur only in the combined sewer system, bypassing of the waste-treatment plant by part of the sewage flow may occur in both combined and separate sewer systems. In some ways bypassing of sanitary flow is more serious because of the higher concentrations of pollutants than are found in combined sewer overflows. However, high concentration may be reduced quickly once the sewage reaches a fairly large body of receiving water. Bypassing can be reduced in frequency by increasing the plant capacity or improving its treatment facilities to handle the more unusual substances entering the sanitary sewer system.

Some schemes to abate pollution due to combined sewer overflows should consider that the capacity of the waste-treatment plant may need to be increased to accommodate the stored overflows when returned for treatment. Capital and operational costs connected with the enlargement of the plant should be included in the economic analysis of these schemes.

3.5. Inspection and Maintenance of Sewers and Their Controls

Many combined sewer overflows are caused by malfunctioning or badly designed overflow regulators. These overflows could be eliminated by better design or by proper inspection and maintenance of the regulators. Part of the costs of better flow regulators is the need to have regular inspection and maintenance, and funds should be budgeted for this purpose. Good planning should prevent the replacement of relatively sophisticated semi-automatic regulators with static regulators of poor regulation ability in order to reduce maintenance costs (22).

The annual costs of regulator maintenance ranges from $300 to $1500 per unit (22), with the lower limit corresponding to simple static regulators and the upper limit corresponding to automatic regulators.

Reduction of Pollutional Loads Caused by Overflows

While the preceeding chapter examined the control of combined sewer overflows by reducing their quantity and frequency, this chapter will deal with methods to reduce the amount or concentration of pollutants contained in overflows by improving the quality of overflows. The overflow quality can be improved in three ways.

a) reducing the input of pollutants into sewage,

b) treatment of overflows,

c) dilution of overflows.

4.1. Reduction of Pollutant Inputs of Combined Sewers

Pollutants reaching an overflow control structure during high flows are derived from three sources which are sanitary flow, urban surface runoff and scouring of sludge which settled in the sewers during the antecedent low flows.

Without changes in sanitary engineering plumbing or practices not much can be done with the sanitary flow input. However the effects of urban runoff and sludge scouring can be reduced.

4.1.1. Reduction of Pollutional Load in Urban Runoff

One of the major pollutants in urban runoff are solids. High concentrations of solids in combined sewers cause many difficulties. The solids tend to form sludge deposits in the pipes which obstruct the flow. Settling of these solids at retention basins and treatment plants pose problems in removal and disposal.

Most of the solids in urban surface runoff originate from street litter. According to a recent investigation (6), on the average, from 0.5 to 8 lbs. of solids per 100 feet of street curb finds its way into the sewer each day. Dust and dirt, containing appreciable amounts of pollutants whose concentrations are usually measured as BOD, COD, nitrogen forms, phosphates and bacteria counts, have been found to be the most important constituents. In periods between rains or between street cleaning the street litter accumulates in the gutter to be washed away during storms and to enter either the combined or storm sewer. Street inlets or catch basins are supposed to trap the street litter so that it does not enter the sewer but is trapped and cleaned out periodically. Experience shows (6), however, that the role of catch basins in trapping solids is rather questionable, because apparently septic liquid and sludge are dislodged and displaced from catch basins during wet weather. Material from catch basins contributes to the first flush of heavily polluted water at the onset of a storm. More frequent and effective street cleaning should greatly reduce the contribution of street litter to the sewer system.

Another significant source of solids in urban runoff is the sediment eroded from urban lands undergoing development. Sediment yields from these areas can be as much as 5-500 times higher than those corresponding to rural areas which retain a natural vegetal cover (37). The rather high urban erosion rates suggest that measures to control soil erosion in towns and cities should be introduced. Common methods of controlling urban soil erosion, discussed in more detail in Reference 37, are the mulching and seeding of the land stripped of vegetation cover during construction, the establishment of vegetation cover, the application of erosion inhibiting chemicals, the construction of diversion ditches diverting surface runoff before it gains sufficient volume and velocity to erode sloping land, the construction of bench terraces along contours and the construction of temporary sedimentation basins. Many of these methods have been already tested in practice and proven to be effective.

De-icing salts and sand spread on the roads during winter are a major source of solid and chemical contaminant. Sand and chemicals entering the sewer can be significant. Chloride concentrations in urban runoff have been reported as high as 25,000 ppm (6) which compares with sea water with concentrations around 33,000 ppm.

In summary, pollutional loads in sewage as well as in combined sewer overflows can be reduced by effective control of urban erosion, improvement of catch-basin and street-cleaning practices and limiting the application of salts and abrasive materials during winter.

4.1.2. Reduction of Sludge Deposits in Sewers

As the storm-water runoff subsides, flow rates and velocities diminish and the sediment transport capacity of the sewage flow is sharply reduced. Consequently, solids being carried by the flow will settle down in the sewer and form sludge deposits. These deposits will be scoured during the initial period of the next storm, causing a high initial pollutional load, which is termed the first flush. Several attempts have been reported to avoid the high pollutant concentrations in the first flush by cleaning sewers during periods between high flows. Under FWQA sponsorship, the feasibility of a periodic flushing system for cleaning of combined sewers was studied (38). Though the flushing action was found promising and test equipment was designed and its cost estimated, the programme was terminated without testing the idea of equipment further.

Particular attention has to be paid to cleaning of combined sewers in a cold climate (39, 40) where large volumes of abrasives are applied to streets during winter. These abrasives largely end up in the sewers, forming deposits, and tend to reduce the sewer capacity necessary to accomodate spring runoff. Consequently sewer overflows may tend to occur more often. A programme of cleaning of combined sewers prior to spring runoff was recommended for the city of Ottawa, in an older district served by combined sewers.

In most cases, periodic cleaning of sewers between storms is not economically justified owing to the high costs.

4.1.3. Pretreatment of Overflows at the Diversion Structure

By pretreatment of combined sewer overflows at the diversion structure is meant the process of retaining the sewage flow with highest concentration of pollutants (mainly solids) in the sewer and discharging the less heavily polluted flow to the overflow. In principle, the objective could be achieved by a selective choice of overflow locations or by fitting the diversion structures with screens, racks, skimmers, etc. Though the benefits of the overflows pretreatment are obvious, it is very difficult, if not nearly impossible, to achieve this goal, since the combined sewage consists of about 99% of water. Improvement of overflow quality (22, 24) was studied for several specially designed overflow regulators, which were described in Chapter 3. Some of these structures utilize hydraulic phenomena and selective withdrawal (vortex regulator, stilling pond regulator), others utilized screens or racks attached to weir regulators. The presently known types (27) bring about only a nominal improvement in the quality of overflows, which hardly justifies the increased cost of these structures.

4.2. Treatment of Combined Sewer Overflows

Treatment of overflows is gaining increasing popularity in control of pollution due to combined sewer overflows. Pollution control schemes based on treatment of overflows have a lower initial capital investment than schemes based on physical storage, but the annual costs of treatment exceed the operational costs of storage. Comparison of the storage versus treatment of combined sewer overflows was presented in a study (41) done in San Francisco. This investigation considered the efficiency of storage as well as of treatment in removal of COD (Chemical Oxygen Demand) and OPP (Orthophosphate-phosphorous) from the overflows. The conclusion was that while storage is more effective in removal of those pollutants whose cumulative (per cent total) emission leads cumulative flow during the storm (see Fig. 7), treatment is more advantageous for removal of pollutant whose cumulative emission lags cumulative flow. It is believed that an optimal system could be devised which would combine the advantages of storage with those of treatment.

Treatment requires the construction of equalizing or detention basins. The costs of storage or detention basins limit their size, and the high discharges responsible for overflows place practical limits on detention times. Short detention times limit the treatment of overflows to physical and physical-chemical methods. Biological treatment is rarely applicable because it requires long detention times.

It should be stressed at this point that while the problem of physical control of overflows by storage and modulation of input-output hydrographs is economic in nature, the problem of the treatment of overflows is a technological one. Basic as well as applied research to investigate the economic treatment of large volumes of moderately polluted overflows or storm water could bring about substantial benefits to pollution control.

4.2.1. Physical-Chemical Treatment

Physical-chemical methods of treatment are especially suitable for treatment of combined sewer overflows because a long detention time is not needed for effective treatment.

4.2.1.1. Disinfection

Disinfection is used to kill harmful bacteria. The percentage of bacteria killed depends mainly on the disinfectant concentration and the contact time, and is usually expressed by an empirical equation (48)

$$E = ktc^n$$

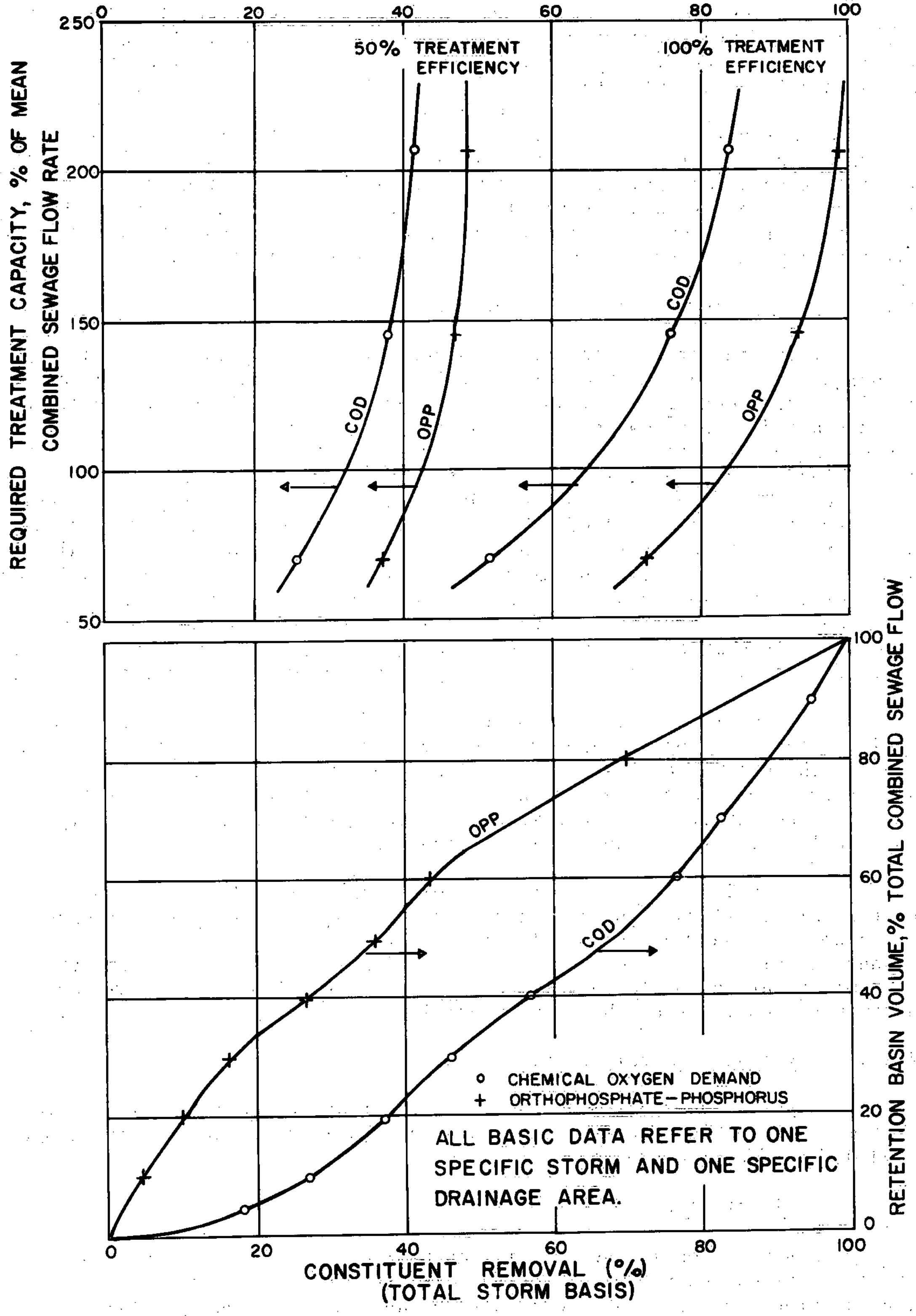


Figure 7. Comparison of treatment vs. storage for efficiency of constituent removal [after (41)].

where k is a coefficient
c is the disinfectant concentration
t is the contact time (min.)
n is the rate constant of the reaction
E is the percent of bacteria killed.

Selection of an optimal combination of disinfectant concentration vs. contact time is an economic problem. For example, longer contact times (say up to 30 min.) require large storage, and therefore high capital costs, but low operational costs because of reduced disinfectant concentrations. Figure 8 gives some typical results for the efficacy of chlorine in killing coliform bacteria. Experience from existing disinfection plants shows that kills as high as 99.99% can be achieved. However, by the time the plant effluent reaches the watercourse, bacteria numbers are on the increase again (42). Some control of the aftergrowth is achieved by maintaining a high residual of the disinfectant in the effluent although this concentration residual will diminish with time and dilution in the water course. Disinfectant residuals however are not always acceptable because they may harm fish or other aquatic life.

High bacteriological counts in combined sewer overflows often make the disinfection of overflows a necessity, in order to protect public health. The cost of disinfecting the overflows can be reduced by using stormholding basins as contact chambers. Disinfection of combined sewer overflows was reported in several References (2, 28, 43, 44, 45) using either halogens or ozone as a disinfectant. Comparison of chlorine and ozone, as disinfectants for combined sewer overflows, is given in Reference 44. The main advantages of chlorine disinfection are its low cost and ability to maintain a residual protection. On the other hand, ozone disinfection requires high capital and operating costs, but ozone is more viricidal than chlorine and can be also used in a treatment process for other purposes than disinfection, namely, odour control and the removal of dissolved organic material. Problems are encountered in the disinfection of overflows because of variations in discharge, variations in acidity (pH) and number of bacteria. These variations require that the supply of disinfectant be variable. Errors result in underkill or the release of too much disinfectant.

In the treatment of combined sewer overflows, the treatment procedures mentioned below are usually supplemented by disinfection of the effluent.

4.2.1.2. Settling

Settling which is also called primary-sewage treatment consists of the separation of the suspended grits from the liquid component of sewage by gravity. It is sometimes advocated as a minimum required treatment of combined sewer overflows prior to their discharge into water courses.

Settling for detention periods of less than 1 hour is not effective in removing BOD, COD, nitrogen, phosphates and solids from combined sewage (46). The same was found in another project (47), in which combined sewer overflows were allowed to settle for periods from 20-180 min. The results from the latter reference are presented in Table 3.

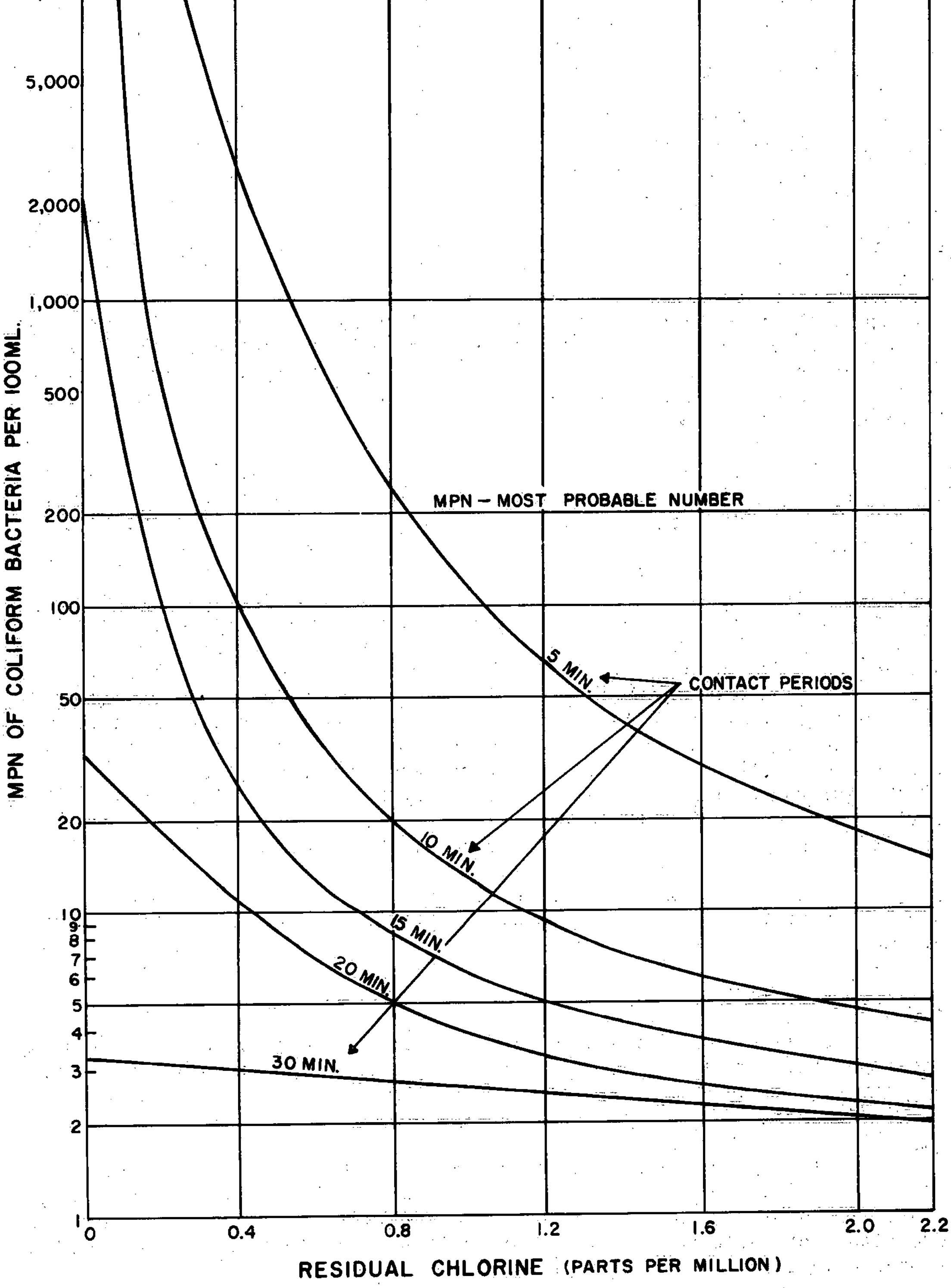


Figure 8. Coliform counts vs. residual chlorine in settled sewage after contact periods of 5 to 30 minutes [after Eliassen and Krieger, Sewage and Industrial Wastes, Vol. 22, Jan. 1950].

TABLE 3

Solids and BOD Removal vs. Detention Time

Pollutant	Detention Time minutes	Removal in percent
Total suspended solids	20 180	15 45
Settleable solids	20 180	20 80
Biological Oxygen Demand	20 180	15 35

4.2.1.3. Chemically-Aided Settling

Chemicals can be added to the sewage to cause flocculation. Flocs settle out more quickly than individual particles and consequently smaller settling basins may be employed.

Various polymeric flocculants for treatment of combined sewer overflows have been tested under EPA/WAO sponsorship (48). Flocculants (for details see Reference 48) were applied in concentrations about 10 mg/l and successfully initiated flocculation and also effectively reduced turbidity for relatively high loadings of suspended solids. The turbidity removal decreased for low concentrations of suspended solids and consequently the final turbidity could be made relatively constant at the exit of the settling basins. Unfortunately, the inadequate behaviour of the test settling basin prevented evaluation of the whole treatment process on a pilot-plant scale. Hence, the flocculants were only tested in a sedimentation tube under conditions of "dynamic" settling (i.e. under influence of low intensity turbulence and currents created by a stirrer). At best flocculants removed up to 80-95% of optical and gravimetric solids in the sedimentation-tube tests.

Improved settling of solids by flocculants has the concomitant problem in the disposal of a greater volume of grit and sludge and the associated costs.

4.2.1.4. Centrifugal Treatment

Separation of heavier suspended particles from liquid media can be accomplished in a relatively short time in centrifugal separators. Two types of centrifugal separators, namely a centrifuge and a hydrocyclon, have been proposed for treatment of overflows (49, 50). The former separator has a high radial acceleration and its initial cost is relatively high. The latter separator is relatively simple, has no moving parts and depends on an induced vortex to obtain a comparatively lower radial acceleration.

Centrifuging of combined sewer overflows to remove heavy solids is proposed in Reference 2 without further evaluation. More information is available on the application of hydrocyclons to combined sewage treatment.

Tests of a hydrocyclon (called VORSEP - vortex separator) are reported in Reference 50. Though the tests were inconclusive, it was estimated that with improved design the hydrocyclon could remove as much as 75% of settleable solids and less than 45% of BOD. The cost of treatment without handling of refuse was estimated as $0.03/1,000 gallons based on a 25 MGD capacity. Due to low BOD removal, the vortex separation was considered suitable only for pretreatment of overflows before further processing.

Though the centrifugal treatment has definite merits, especially due to small space requirements and short detention times, operational as well as disinfection costs may be prohibitive in some cases. Cost of disinfection is relatively high since special contact chambers, serving only for the disinfection, have to be incorporated into the scheme.

4.2.1.5. Microstraining

The basic component of the microstraining system (illustrated in Fig. 9) is the microstrainer, which is a horizontal drum filter with a specially woven wire fabric of stainless steel as the filter medium. During operation, the microstrainer is submerged in the flowing sewage to approximately 2/3 of its depth. The influent enters the upstream end of the drum and flows radially outwards through the microfabric, leaving suspended particles on the inner side of the microfabric. This build up of solids is flushed by backwash jets into a refuse trough located inside the drum above the sewage level. Ultraviolet irradiation is used to inhibit growth and formation of organic and bacterial slimes.

The microstraining system, as described above, was installed in Philadelphia (44) on a combined sewer overflow. The results of treatment experiments are summarized as follows.

TABLE 4

Solids Removal by Microstraining

	Type of Microfabric	
	Mark 0 (23 micron)	Mark 1 (35 micron)
Total solids removal under high loading	78 - 98% (over 91%)	over 44%
Total solids removal under low loading	62 - 96% (over 80%)	
Removal of volatile suspended solids	68; 71; 71%	over 47%

These results were achieved with the original design of microstrainer. The final, improved version of microstrainer was tested only with the finer microfabric (i.e. Mark 0).

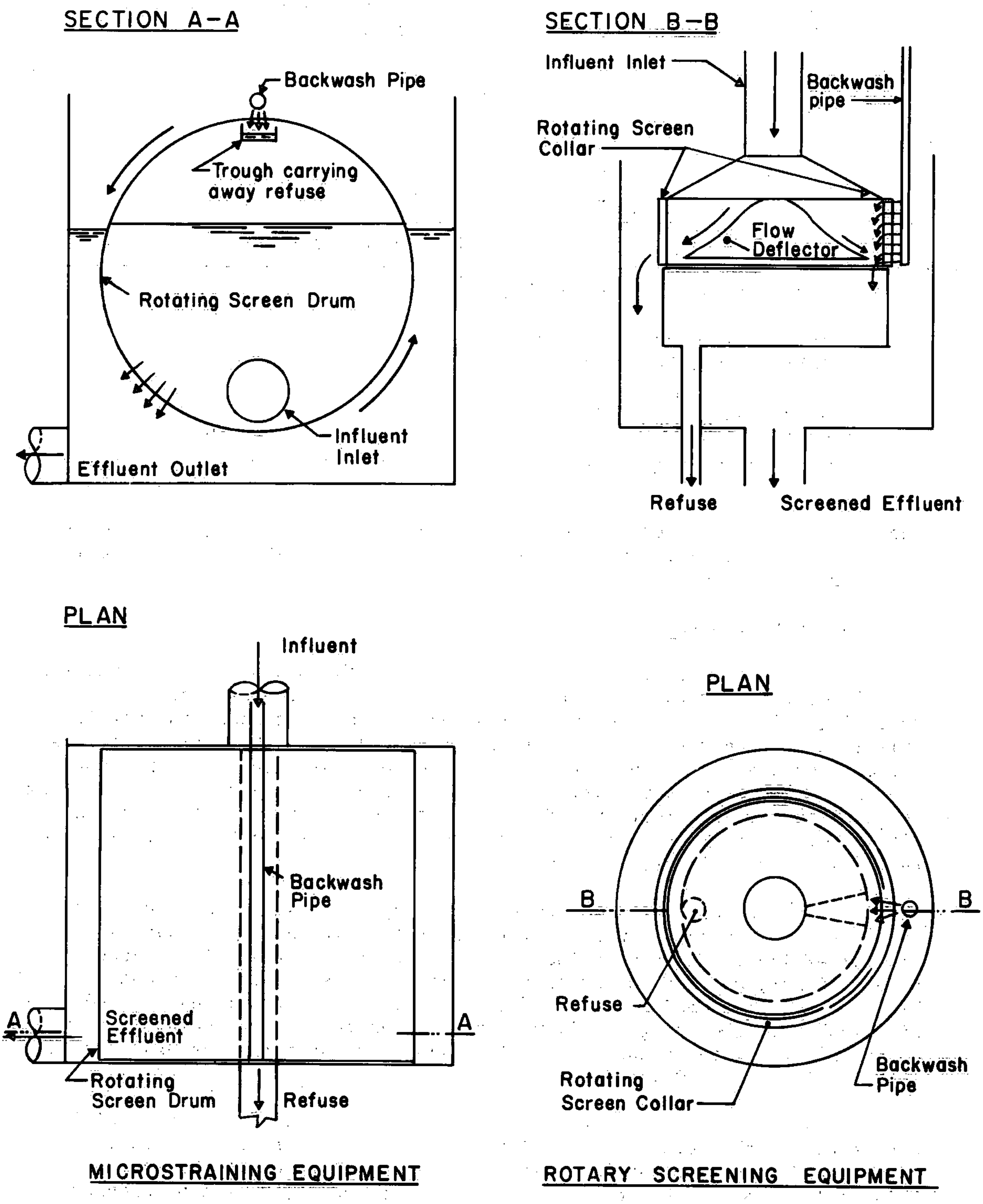


Figure 9. Microstraining and rotary screening equipment [freely sketched after (44) and (51) respectively].

Bacteriological counts across the microstrainer were not consistent. In some cases the counts were reduced but in others were increased. Cost analysis of microstraining are shown in Table 5.

TABLE 5

Capital Costs of Microstraining

	Capital Cost per Acre of Drainage
1. Bar screening and microstraining	$10,200
2. Bar screening, microstraining and chlorination @ 5-20 ppm	$11,200
3. Bar screening, microstraining and ozonation @ 5 ppm	$19,800

The above costs included neither cost of land nor engineering fees and are in 1969 prices (US $). In many localities the costs estimated here would make screening prohibitive.

4.2.1.6. Rotary Screening

The rotary screening unit is similar to the microstrainer. Whereas the microstrainer rotates about the horizontal axis, the drum of a rotary screening unit rotates about a vertical axis. Rotation about the vertical axis leads to generation of centrifugal forces driving the influent across the mesh boundary. In the inflow part, the vertically entering influent (see Fig. 9) hits a stationary distribution dome, which diverts the jet from an axial to radial direction. The deflected jet strikes a collar screen with a relatively high velocity. As in case of the microstrainer, backwash the collar screen is provided for.

A scale model of a rotary screening system was tested in Portland using diluted sanitary sewage as influent (51). It was found that the removal efficacy of the unit increases as the mesh of the collar screen becomes finer, and the concomitant head loss across the collar becomes higher. The final modification of the rotary screening unit was fitted with mesh having openings of 74 microns in diameter and was able to remove up to 99% of floatable and settleable solids, 34% of total suspended solids, and 27% of Chemical Oxygen Demand (COD).

The main setback of the tested system was a rather short life expectancy of the screens - only 4 to 12 hours. Therefore, the final testing (52) was aimed at increasing the life expectancy of the screens. This goal has been achieved by using coarser screens (105 micron openings), reducing the rotational velocity and reducing the velocity of the jet impinging on screens. The ultimate screen life varied from a minimum of 190 hours to a maximum of 516 hours with an average of 346. However, the hydraulic capacity of the system was reduced by about 20%, and the removal of pollutants was reduced by about 40% as compared to the original rotary screening unit.

Rotary screening systems deserve much fuller investigation and studies since the idea has considerable potential for rapid processing of diluted storm water or combined sewer overflows.

4.2.1.7. Filtration

Several attempts to filter combined sewer overflows are reported in literature (45, 50, 53). It is believed, that filtration of combined sewer overflows is rarely feasible, because the solids plug the filters relatively quickly. Plugging could possibly be prevented if the solids could be removed prior to the filter.

Tests on a filter formed by fibers wound in a predetermined pattern and bound in place by resins are reported in Reference 53. Up to 62% reduction of suspended solids in the filtrate were found but the tests were rather limited and sustained runs were not done.

Another study (45) reports on laboratory tests of filtration of synthetic combined sewage by multi-media and fiberglass filters. The multi-media filter column consisted of the following layers: 30" of anthracite (particle size 2.0-2.8 mm), 15" of sand (.5-1.0 mm), 9" of fine garnet (.35-1.0 mm), 3" of coarse garnet (1.4-4.0 mm), 3" of fine gravel (4.0-8.0 mm), and 6" of medium gravel (8-16 mm).

The results of filtration tests are presented in Table 6.

TABLE 6

Results of Filtration Tests using Fiberglass and Multi-Media Filters

	Multi-Media Filter	Fiberglass Filter
Flow rate (gpm/sq.ft.)	5	5
Run time (hours)	1	9
COD		
Concentration in feed (mg/l)	159	197
Concentration in effluent (mg/l)	48	58
Percent removal	70	70
BOD		
Concentration in feed (mg/l)	31.7	48.0
Concentration in effluent (mg/l)	6.0	12.0
Percent removal	81	75
Suspended Solids		
Concentration in feed (mg/l)	580	536
Concentration in effluent (mg/l)	86	8
Percent removal	85	98

After one hour, the excessive head loss across the multi-media filter prevented further operation, whereas the fiberglass filter was operating up to 9 hours. After 9-hour operation, however, the fiberglass filter could not be fully backwashed, and any subsequent runs were only of short duration because of the rapid increase in head across the filter.

Difficulties connected with the backwashing of filters are alleviated in filtration aided by ultrasonic energy. Such a system was tested in Atlanta (50) using sanitary sewage diluted by fresh water. The filtration unit consisted of 20 plastic filter elements each having an area of 0.8 sq. ft. and mesh openings of 35 microns. The total plant capacity was 250,000 gpd. Reduction of the cake buildup on the filter was achieved by a momentary stoppage of the flow for one second every 10 to 20 seconds, with simultaneous application of ultrasonic energy to the interior of the tank which dislodged the material adhering to the filter. The study demonstrated that the polyethylene filter tested was not suitable for the treatment of sewage containing rust particles because these effectively block the filter elements. The manufacturer of the equipment attributed this plugging to the tendency of polyethylene to absorb rust due to polyelectrolytic effect, and suggested that the problem could be avoided either by using filter elements made of stainless steel, or by pretreatment of the sewage in a cyclon. Preliminary results indicated that with concentrations of BOD and suspended solids of about 100 mg/l in the influent, or less, ultrasonically aided filtration with 35 micron plastic filter elements might reduce BOD and suspended solids by 50% provided no rust particles are present. The cost of filtering would be about $0.08 per 1000 gallons.

The need for filter backwashing can be eliminated by using a disposable filter medium. In one reported case (54) the feasibility of using lump coal as filter medium was studied. Replacement of the filter bed would be required about 6 times per year.

Though the above filtration methods seem to be promising as a means of treating combined sewer overflows, none of the methods can be recommended for application without further investigation.

4.2.1.8. Dissolved-Air Flotation

Dissolved-air flotation has been proposed by several investigators (45, 55, 56) as part of the total treatment of combined sewer overflows. The main purpose of the flotation is to increase the content of dissolved oxygen in the effluent and flotation is usually preceded by primary treatment. Dissolved-air flotation systems use either air dissolving tanks (45) or U-tube aerators. U-tube aerators, consisting of a vertical U-shaped conduit and a device introducing air or oxygen into the down-leg of the conduit, have many advantages, namely, long contact times, effective utilization of oxygen deficits, and low capital and operating costs due to the lack of moving parts.

The economical feasibility of dissolved-air flotation systems was studied in Reference 55. These systems were found economical for treatment of combined sewer overflows up to capacities of 8 MGD. The cost of treating overflows by U-tube aerators having 5 MGD capacity was estimated as $2,600 per year, with an initial capital outlay of $25,000 (45).

4.2.2. Biochemical Treatment

As mentioned before, biochemical treatment is not often feasible for treatment of combined sewer overflows, because the long detention times required need the construction of large storage basins.

Conventional biochemical oxidation was proposed for treatment of combined sewer overflows in Cleveland (57). The treatment would take place in a large waste-stabilization basin or sewage lagoon of 30,000 ac-ft storage, which would be built off-shore in Lake Erie. The design considered photosynthetic activity in the upper portion, nutrient uptake by organisms, algal removal and mineral precipitation. The total cost of this system was estimated to be $83 million, as compared with $948 million for sewer separation.

A similar off-stream sewage lagoon was found to be the most economical and effective choice to abate pollution due to overflows at Bucyrus, Ohio (58). In Reference 58, the degree of treatment of the sewage was expressed as the percent of BOD remaining in the sewage after a given number of days:

$$\text{BOD RESIDUAL } (\%) = 100 - (1 - 10^{-kt})\,100$$

where t............duration of treatment in days.
k............is the rate of reaction constant of the degradation of organic matter.

An examination of this equation indicates why sewage lagoons are not often feasible for the treatment of overflows. For $k = 0.10$ which represents the upper limit, it requires 4-6 days to reduce BOD by 50 and 60% respectively.

The variable k is a function of the BOD concentration and is proportional to it and consequently the process slows down as the quality of the sewage improves.

To avoid large storage volumes, it would be preferable to treat only that part of the overflow which is most heavily polluted. However reserve storage is required especially where a second storm could occur within 4-6 days of the first.

Little is known about the treatment of combined sewer overflows by highrate, rotating biological contactors (59). These contactors do not require long detention and can achieve BOD removals as high as 90% (60).

4.2.3. Combinations of the Above Methods

Many processes are not completely effective or are only able to deal with one pollutional component, and consequently it is sometimes feasible to combine two or more treatments. Several total treatment schemes from Reference 44 are shown in Figures 10A and 10B.

4.3. Dilution of Overflows

Dilution of overflows or flow augmentation is a method of controlling pollution from combined sewer overflows by providing sufficient dilution water to maintain a desired low concentration of pollutional constituents in the receiving water body. The water needed for the dilution of overflows has to be stored in a reservoir and its delivery has to start at the time of overflow.

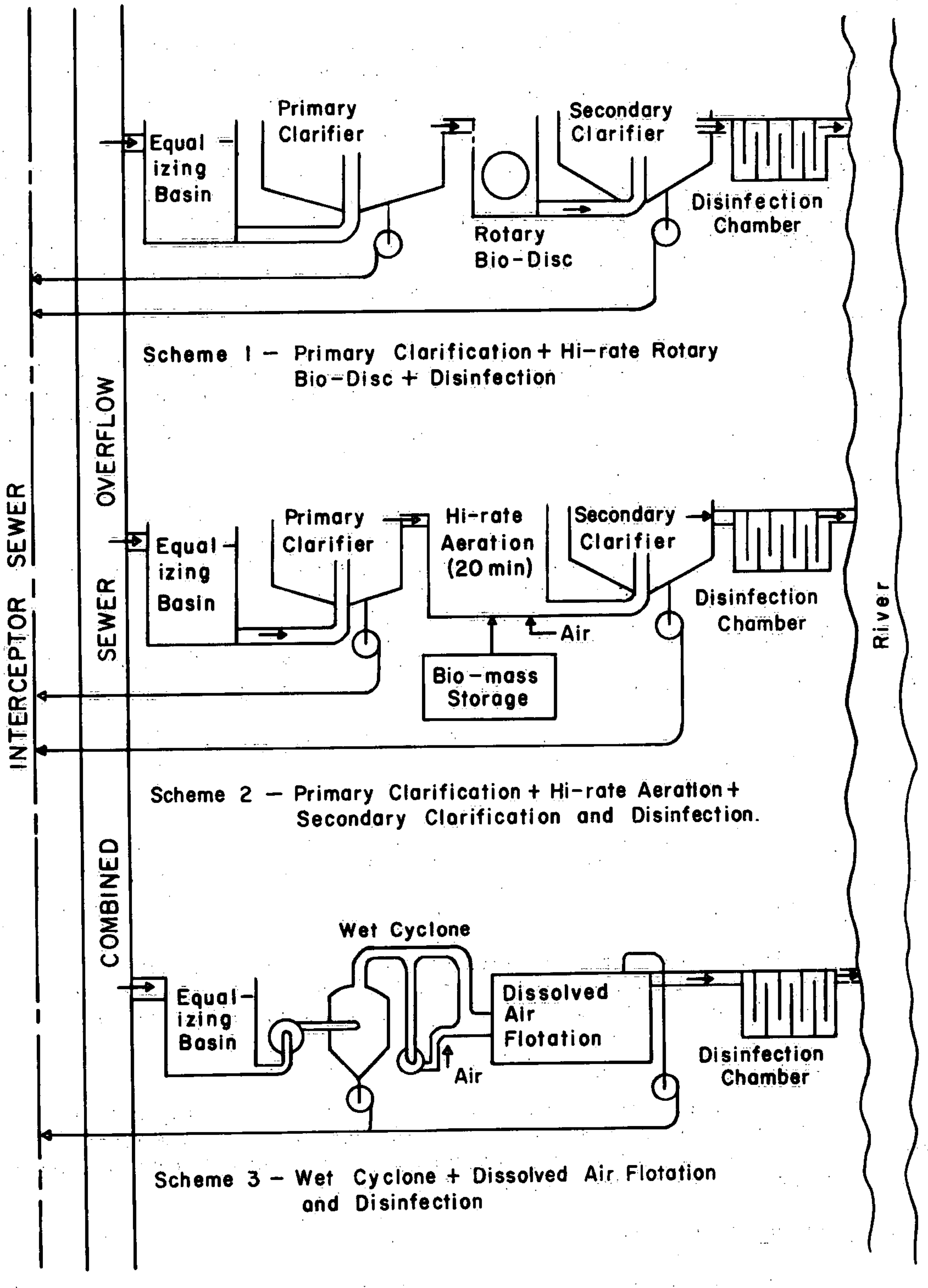


Figure 10A. Possible schemes for treatment of combined sewer overflows [after (44)].

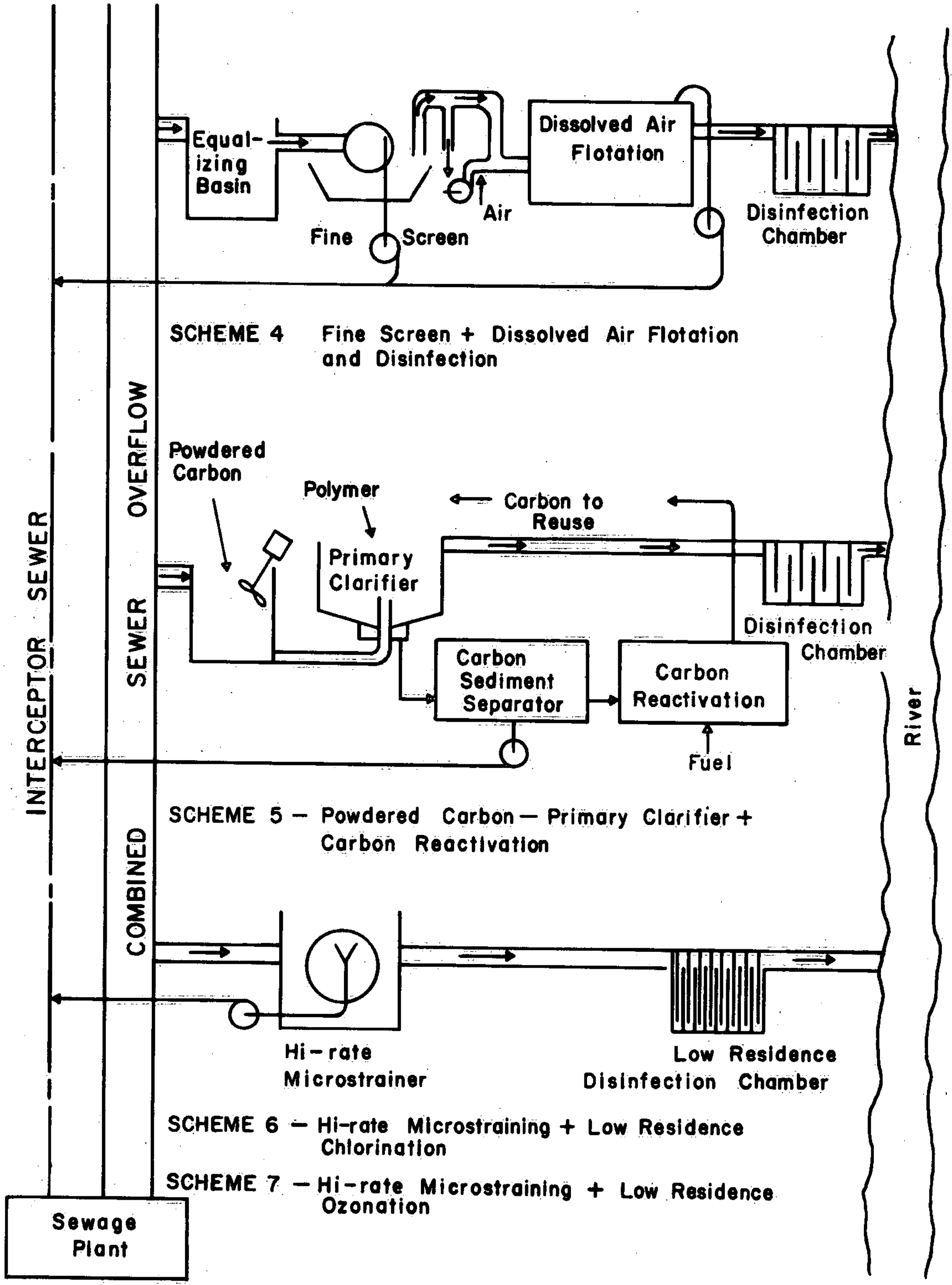


Figure 10B. Possible schemes for treatment of combined sewer overflows [after (44)].

Though this method may be considered as one of the possible abatement schemes (58), it would be rarely feasible due to technical problems and expenses connected with the maintaining of a large storage of dilution water.

Since the dilution of overflows does not reduce the cumulative amount of pollutants in the overflow, this method is not applicable in cases when not only the concentration but also the total load of pollutants are of primary concern.

Reduction of Overflow Quantity and Its Pollutional Load

The pollutional abatement methods discussed in this Chapter are based on the combination of physical storage and treatment of combined sewer overflows.

5.1. Storm Holding Tanks

There are three synonomous expressions referring to a facility for storage of combined sewer overflows; namely retention tank, detention tank, and storm holding tank. In practice these names refer to similar installations or function. Generally the main function of a retention tank is to modulate flow, the function of a detention tank is to detain flow volumes for some time necessary for treatment. In practice, retention or detention tanks fulfil both functions and in that case are often termed storm holding tank. This latter expression will be used throughout this Chapter. Storm holding tanks modulate flows and provide some of treatment by permitting solids to settle out. Properly designed and maintained storm holding tanks are effective in pollution control of combined sewer overflows and have proved this effectiveness in many locations. Several design and operational features of these tanks are discussed below. For further information, the reader is referred to the bibliography.

5.1.1. Sizing of Storm Holding Tanks

Selecting the size of storm holding tanks is not simple and no routine procedure has been established.

Basically, the overflow which goes directly to the water course should not add more pollutant to the water course than can be tolerated over a time period. Acceptable volumes, quality and overflow frequencies are questions which cannot be dealt with here if in fact they can be determined except in subjective terms. Be that as it may, one can state that

$$P = \sum_{1}^{n} M_i \qquad \text{.....(5.1)}$$

where M is the total weight of pollutant in the overflow
n equals the number of overflow events per year
P is the total weight in one year.

Adding a storage tank to a system reduces the total weight P released directly and may, if the tank is large enough, reduce the number of overflow events.

The value of M is given by

$$M = \int_{t_1}^{t_2} [q(t)-q_p]\ p(t)\ dt \qquad \text{.....(5.2)}$$

where $q(t)$ is the total flood flow ft^3/sec
q_p is the maximum flow into the plant
$p(t)$ is the pollutant concentration in lb/ft^3
t is the time
t_1 t_2 start and end of overflow event.

Both p and q vary with time in a way which is a function of the sewer system network, the storm spatial and temporal distribution and the overflow control structure. Figure 11, which has been adapted from Reference 11 shows typical functions of p (t) and q (t) using BOD as the indicator of water quality. Notable is the high concentration "p" of BOD at the outset caused by the accumulated sludge in the sewers which is washed through by the rapidly increasing discharge.

The total volume of water which passes over the diversion structure is given by

$$V = \int_{t_1}^{t_2} [q(t)-q_p]\, dt \qquad .....(5.3)$$

If V_T = the total volume overflowing when (t_2-t_1) equals total time of the overflow, then it is possible to plot V/V_T against the percentage of the total BOD as has been done in Figure 12.

In Figure 12, curve A, a storage tank having a volume of one third of V_T will in this case trap about one half of the pollutants expressed as BOD. Note if a tank is designed for V_T and an overflow having $2V_T$ occurs then only about one fifth of the pollutant is trapped in the storage.

The selection of a design overflow volume and its accompanying frequency of occurrence is a very difficult question. Some authors (2) recommend periods of 20 years where polluted overflows could cause serious effects. Others (2) recommend return periods of 10, 5 or 1 year. In one instance (11) the return period was only 2 weeks, since these storms contained over 80% of the annual output of BOD.

Return periods of overflows are often associated with the return periods of rainstorms. But there is often a poor correlation between storm events and overflow events. A standard procedure to select the optimum overflow volume which should be trapped is in general not available. Probably individual systems will require investigation in order to obtain some insight into their hydrologic, hydraulic and pollutional characteristics.

5.1.2. Treatment and Storm Holding Tanks

After all or a portion of the overflow has been trapped in the storm holding tank there remains the problem of treating the overflow sewage.

Water quality improves in the tank because solids settle and the overflow tank becomes in effect a primary clarifier or grit chamber. Several investigators (46, 47) have shown that the detention time should usually range from 60 to 180 min. for effective improvement in water quality. Data from Reference 47 has been plotted on Figure 13 to illustrate the removal of solids and reduction in BOD for storm holding tanks at Columbus, Ohio. It seems that, for these tanks, little benefit is gained by extending

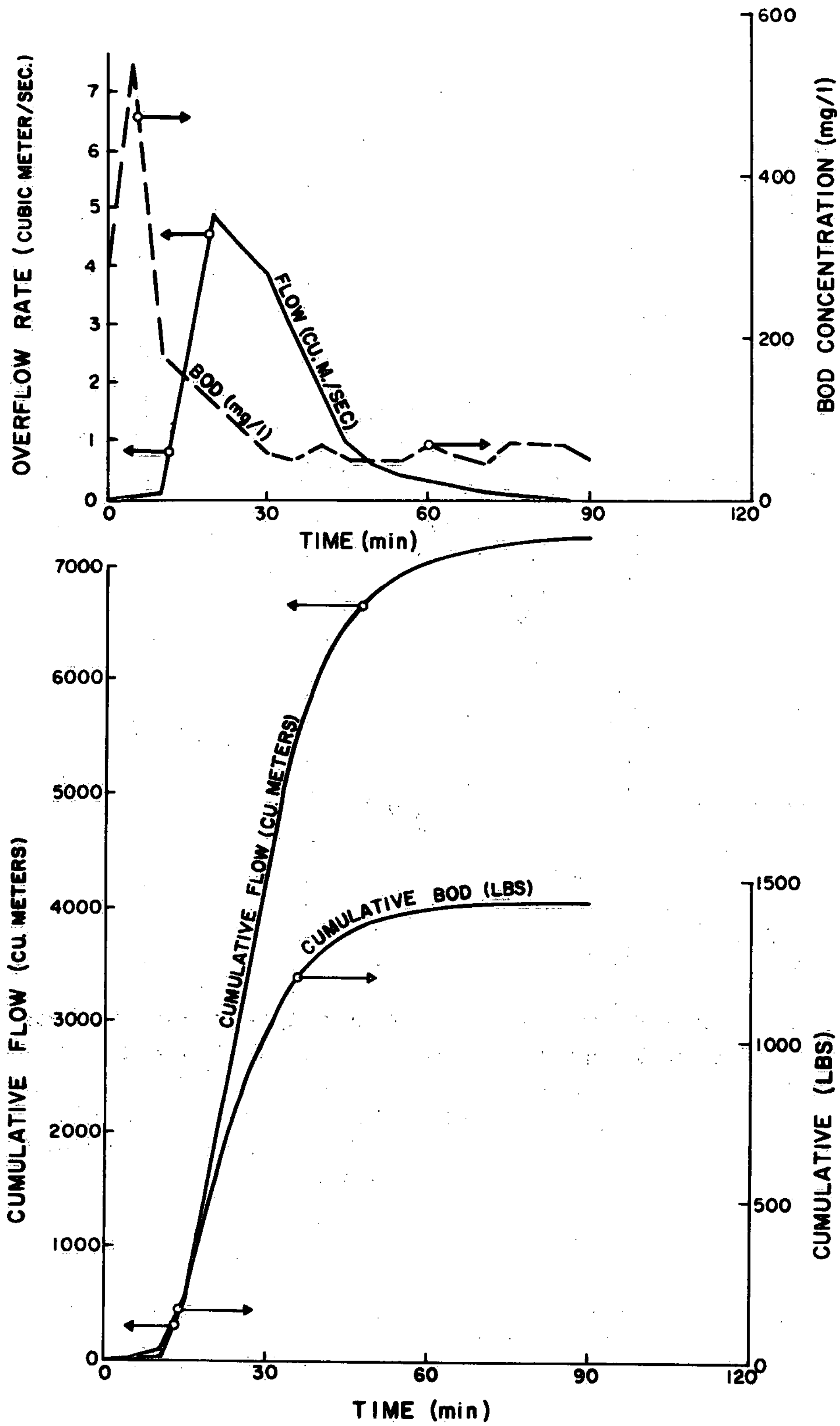


Figure 11. Typical variation of flow and BOD for a combined sewer overflow [data after (11)].

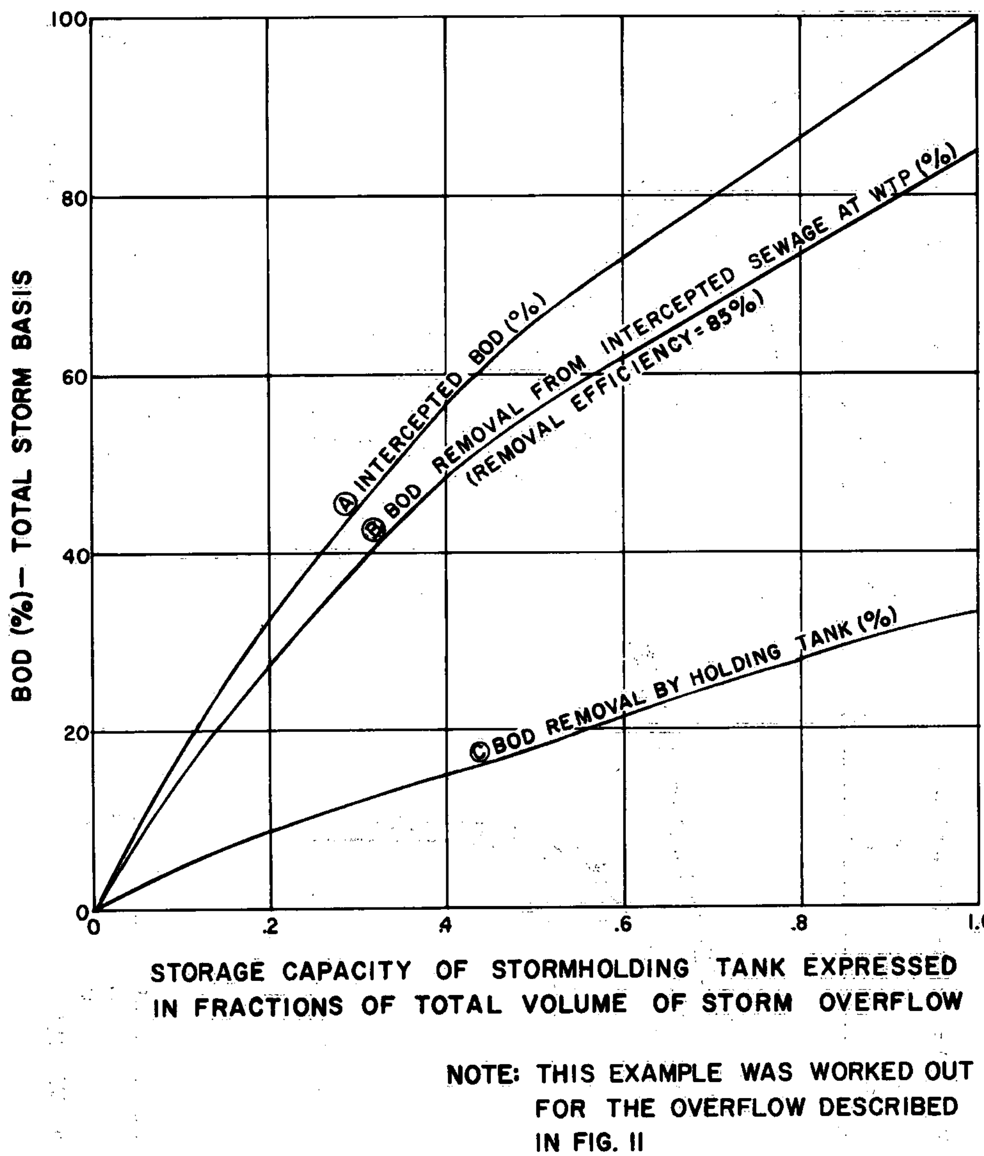


Figure 12. Interception and removal of BOD by storm holding tanks of various capacities.

the detention time past 100 minutes. Thus in design, the choice of tank size is greatly influenced by the selected or desirable improvement in BOD before discharge to the watercourse. Oversizing the tank does not yield a corresponding increase in water quality improvement but will reduce the number of events where overflow exceeds the volume of the tank.

Using the illustrated data of Figures 11 and 13, the total amount of BOD removed as the size of the tank increases was computed and plotted as curve C on Figure 12. The difference between curves A and C shows the amount of BOD which would be discharged directly to the watercourse. It is clear that storm holding tanks do improve the water quality but at best about 2/3 of the total overflow BOD is discharged directly to the watercourse, though this discharge may be spread over a time period.

Increasing detention times to try to improve the water quality may be defeated by two factors.

One, the probability of a second overflow event occurring before the tank is emptied may result in direct overflows to the watercourse. Two, the sewage in the tank may become oxygen depleted because of the lack of aeration. Artificial reaeration is possible but may bring settled material back into suspension.

In large urban areas several tanks may be employed. An economic analysis of a system of tanks in San Francisco may be found in Reference 2.

5.1.3. Costs

Very little information on capital costs was found in the literature. In Reference 2 the following information was given.

TABLE 7

Storm Holding Tank Costs for 1964-65

Tank Capacity in Millions of Gallons	Cost in Million Dollars per Million Gallons of Capacity
0.7	0.6
9.5	.55
12.0	.65

Since 1964 the Engineering News Index has risen 60% so that todays costs may be considerably higher.

5.1.4. Operation and Maintenance of Storm Holding Tanks

Sludge deposited in the tanks needs to be removed to avoid the development of bad odours (47) and severe pollution in subsequent flows. Mechanical equipment is usually installed (2, 47, 61, 62) to remove the

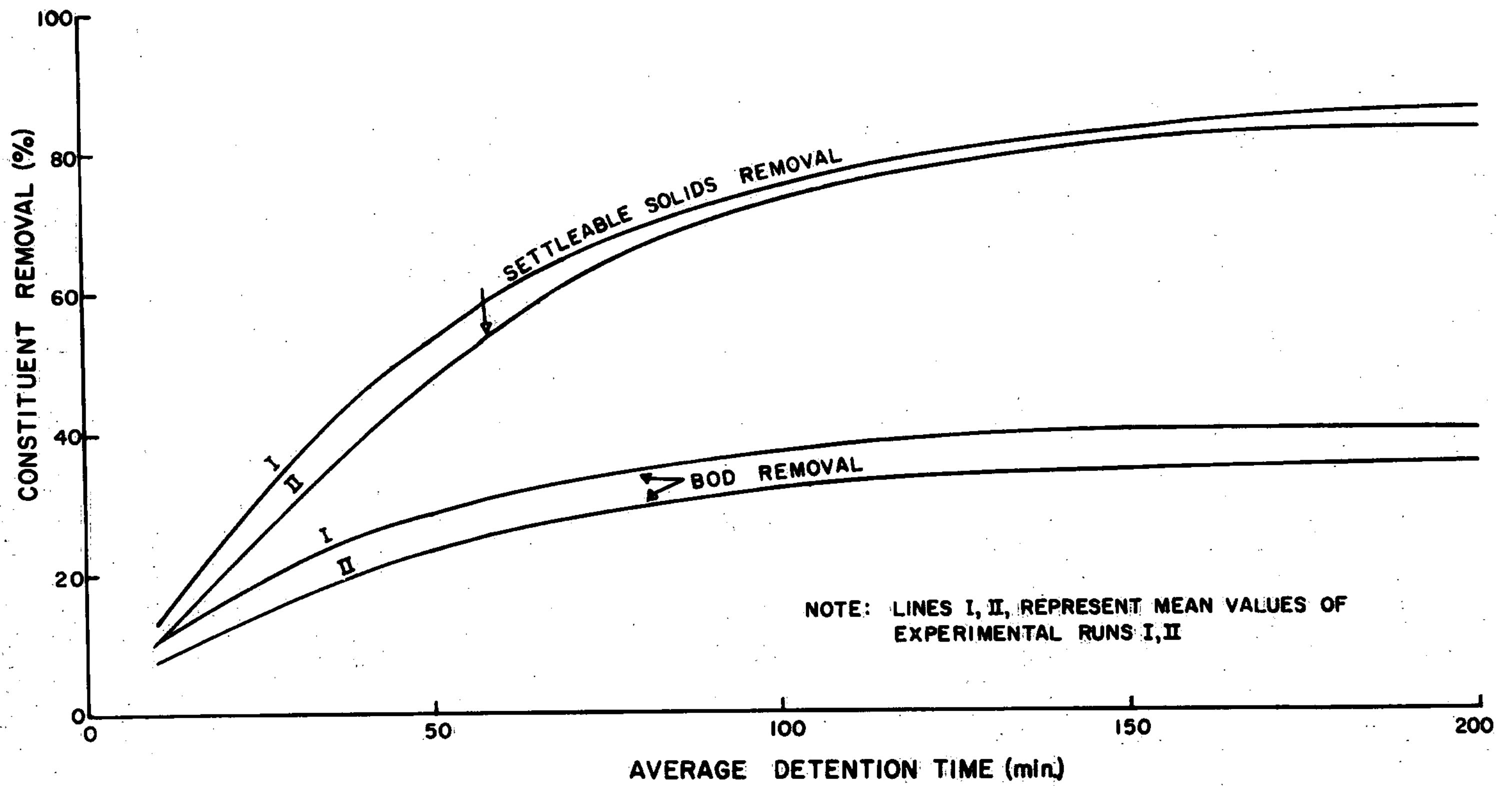


Figure 13. Settleable solids and BOD removal vs. detention time in a holding tank [after (47)].

deposited solids from the tank. Where it is feasible, the tank can also be flushed with water.

Usually the installation of fully automated sludge removal equipment is not justified because of the intermittent operation.

In case of large urban drainage areas, more than one storm holding tank may be required. This further complicates the control of overflows, since these tanks could be in various locations, having various capital and operating costs, etc. Such a problem was analyzed in detail in Reference 2, and theoretical findings were applied to the problem of overflows in San Francisco. An optimal solution to the problem of control of overflows was found by minimizing the total cost of the scheme to meet predetermined criteria for water quality in a watercourse for a design storm of selected frequency.

5.2. Storm Holding Tanks with Treatment of Effluent

As shown in paragraph 5.1 holding tanks are not very effective in the removal of pollutants. Therefore, it is probably necessary to provide for additional treatment of the stored sewage in order to meet effluent standards. Treatment may take place in the tank itself (i.e. disinfection, chemical precipitation), or the tank effluent may pass through the plant later.

Conclusions and Recommendations

6.1. Combined sewer systems suffer overflows during storms when the peak flows are often two orders of magnitude greater than the normal dry weather flow. Untreated sewage is released to the watercourse during the overflows.

Separated sewer systems may also release untreated sewage. Firstly, the plant may be bypassed because of plant breakdown or because of excessive infiltration during storms. Secondly, the storm water contains substantial quantities of pollutants which are passed directly into rivers and lakes without treatment.

6.2. Overflow events from combined sewers may be reduced in two ways.

1. Reducing the total volume.

2. Reducing the peak discharge by smoothing hydrograph.

6.3. The total volume of runoff entering the sewer may be altered by changing regulations governing connections. For example:

1. Stopping the practice of storm connections from domestic houses.

2. Diverting runoff from parking lots into sink pits rather than into sewers.

3. Reducing the areas which are covered with impermeable surfacing to reduce the runoff and encourage infiltration.

   (There seems a research opportunity here to look for or develop a ground covering which would serve the same purpose as asphalt but remain permeable or alternatively retard runoff)

4. Reduce infiltration from ground water. Methods of sealing existing sewers are needed.

6.4. Peak discharges could be reduced by basically introducing storage into the system.

For example:

1. Reduce the number of inlets to storm sewers so that increased storage must be developed in gutters.

2. Construct temporary lagoons or storage tanks to relieve flow in downstream pipes.

3. Raise by specification the inlets to roof storm drains on industrial buildings.

6.5. Even with a number of remedial steps to reduce the hydrograph volume, peak discharge overflows will still occur, and adequate protection of the environment may require treatment of overflows. Traditional methods of treatment requiring rather slow biological action, long detention times and consequently considerable storage are not suitable for dilute, large volume overflows.

There is a great need to develop high-speed treatment methods for sewage, especially highly-diluted sewage flows which occur during overflows of combined sewers. The *development of such systems ought to receive the highest priority.* Some of the more direct methods have already been attempted; e.g. Centrifuges, high-speed screening, reverse osmosis, high-speed filtering.

Other ideas such as irradiation, electrophoresis, the employment of ozone and magneto-hydrodynamic effects deserve further exploration. Most of these ideas could be effectively studied in the first instance in a hydraulic laboratory or pilot plant.

6.6. Control of flows in diversion structures is not very reliable at the moment. Either the simple structure does not meet all flow conditions or the more complicated device requires constant maintenance. There is a need to develop designs and equipment which will be cheap and reliable thus encouraging good regulation. The fluidic type regulator developed recently in the U.S.A. seems to be promising in this regard.

6.7. The expected flows in either combined or storm sewers are not easily measured nor deduced from rainfall.

There is a need to collate hydrologic information and relate this to sewer flows so that economic and reliable designs can be implemented. Regulation schemes need reliable data if economical designs are to be worked out by engineers.

So far, numerous attempts to establish a correlation between the pollutant content in sewer overflows and the hydrologic and demographic characteristics of urban drainage areas have not been very successful.

6.8. There is a substantial requirement to develop methods, either new types of pipes, or new joints to reduce the infiltration of groundwater into sewers. On average 15%, of the dry weather flow is infiltration. Consequently this extra flow is reflected in higher costs for pipes, treatment plants, chemicals and also indirectly in that it reduces the sewers capacity to accept additional connections. (Note that water supply pipes also leak and lose about 10-20% of the average daily demand.)

In old existing pipes, improvement in operations would be obtained if inexpensive methods to seal installed pipes could be developed.

6.9. The most likely alternative to separation of systems is to provide temporary storage for storm overflows so that overflow events (that is events which will exceed the capacity of the storage) will occur so rarely as to be negligible.

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